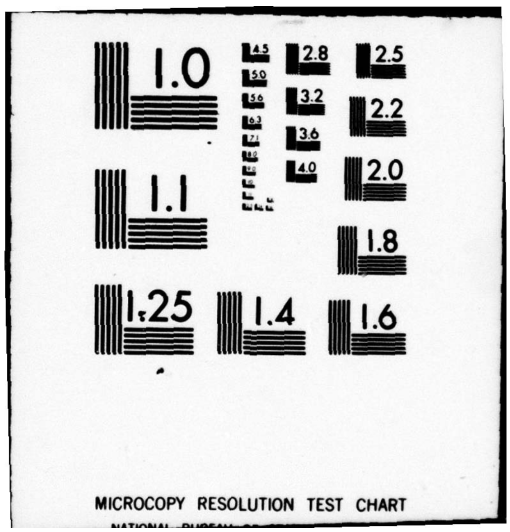
AD-A070 758 ARMY TEST AND EVALUATION COMMAND ABERDEEN PROVING GRO--ETC F/G 19/5
ARMY AIRCRAFT FIRE CONTROL SYSTEMS PERFORMANCE EVALUATION.(U)
JUN 79

UNCLASSIFIED TOP-7-1-006 NL

1 OF 1
AD
A070758

END
DATE
FILMED
8-79
DDC


MICROCOPY RESOLUTION TEST CHART

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(12)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TOP [redacted] 7-1-006

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): [redacted] (6) ARMY AIRCRAFT FIRE CONTROL SYSTEMS PERFORMANCE EVALUATION.

5. TYPE OF REPORT & PERIOD COVERED: Final

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s):

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
U.S. Army Yuma Proving Ground
ATTN: STEYP-MAA
Yuma, AZ 85364

383 350

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: DARCOM-R 310-6

11. CONTROLLING OFFICE NAME AND ADDRESS:
U.S. Army Test and Evaluation Command
ATTN: DRSTE-AD-M
Aberdeen Proving Ground, MD 21005

12. REPORT DATE: (11) 1 June 1979

13. NUMBER OF PAGES: 79

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

LEVEL II

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: NA

16. DISTRIBUTION STATEMENT (of this Report):
Approved for public release; distribution unlimited.

DDC RECEIVED JUL 2 1979 C

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
(14) TOP-7-1-006

18. SUPPLEMENTARY NOTES:
(12) 79 p. (9) Final rept. on test operations procedure.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

Aircraft armament	Performance	Evaluation
Aircraft weapons	Effectiveness	Weapon system
Accuracy	Helicopter weapons	Fire control
Dispersion	Guns	
Ballistics	Rockets	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This TOP provides an overview of the testing required for evaluation of the performance or effectiveness of modern Army aircraft weapon systems. A chart of test inputs to an aircraft armament system effectiveness evaluation is provided. Test and analysis procedures for accuracy and dispersion inputs are presented in detail.

047 750

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

DRSTE-RP-702-106 1 June 1979
Test Operations Procedure [redacted]
AD No. 9-1-006

ARMY AIRCRAFT FIRE CONTROL SYSTEMS PERFORMANCE EVALUATION

Approved for public release; distribution unlimited.

1. SCOPE

1.1 OBJECTIVES

This TOP provides an overview of the testing required for evaluation of the effectiveness of modern Army aircraft weapons systems. Detailed procedures are provided for certain tests; reference is made to other tests beyond the scope of this TOP. The principal paragraphs and appendices are listed in the Table of Contents.

1.2 LIMITATIONS

Because of the extreme diversity of aircraft armament systems it is not feasible to provide specific test procedures in a single TOP. Topics which have not been addressed in this TOP are:

Night Vision Sights
Laser Target Designators and Trackers
Munition Dispensing Systems
Automatic Weapons Qualification Tests
Guided Missile Systems
Reliability Test and Analysis of Aircraft Armament Systems
Maintenance Evaluation of Aircraft Armament Systems
Human Factors Evaluation of Aircraft Armament Systems
Terminal Effects Evaluation of Aircraft Armament Munitions

The general terms "launcher" and "munition" are used in place of more specific terms such as machine gun, grenade launcher, rocket launcher, missile launcher, and cartridge, rocket or missile. Care should be taken that procedures defined herein are applicable to specific test items.

This TOP is limited to the test methods for collection of data for a system evaluation. Procedures for analysis and evaluation of system effectiveness are beyond the scope of this TOP except as related to test data requirements.

1.3 DATA REQUIREMENTS FOR SYSTEM EFFECTIVENESS

A thorough evaluation of an aircraft armament system will consider some form of effectiveness model. The effectiveness model and general data requirements will be generated by the agency performing the evaluation. The test agency will be called upon to supply data for input to the effectiveness model. That data will include combined effects of system availability, dependability, and capability (Ref AMCP 706-191)[1].

Even though the analysis of system effectiveness is beyond the scope of this TOP the test agency should be aware of the approach that may be used. Also, the test agency should perform the preliminary, partial, or tentative analyses necessary to determine data accuracy requirements and to assure validity of test data.

An "end game" analysis of aircraft armament effectiveness may be used to determine test data requirements. One or more measures of effectiveness (MOE) are selected upon which to base the system evaluation. An effectiveness model is created which identifies the factors upon which that effectiveness depends. See Figure 1-1 for an example.

The input data are obtained from several sources. Estimates and hypothetical data may be used but major decisions should consider as much firm test data as possible.

Separate effects should be evaluated where possible so that the sensitivity of the MOE model to these effects can be shown. For example, poor system reliability may have a very adverse effect on the single MOE. However, if that poor reliability is caused by a chronic incompatibility between automatic weapon and feed system, the detail model will show the improvement in effectiveness that can be gained merely by correcting the weapon subsystem deficiency.

Usually the developer is most interested in component or subsystem performance as an area for product improvement. The evaluator will be interested in overall system effectiveness. The test agency must provide data for both.

[1]AMCP 706-191. Engineering Design Handbook, System Analysis and Cost Effectiveness, 1971.

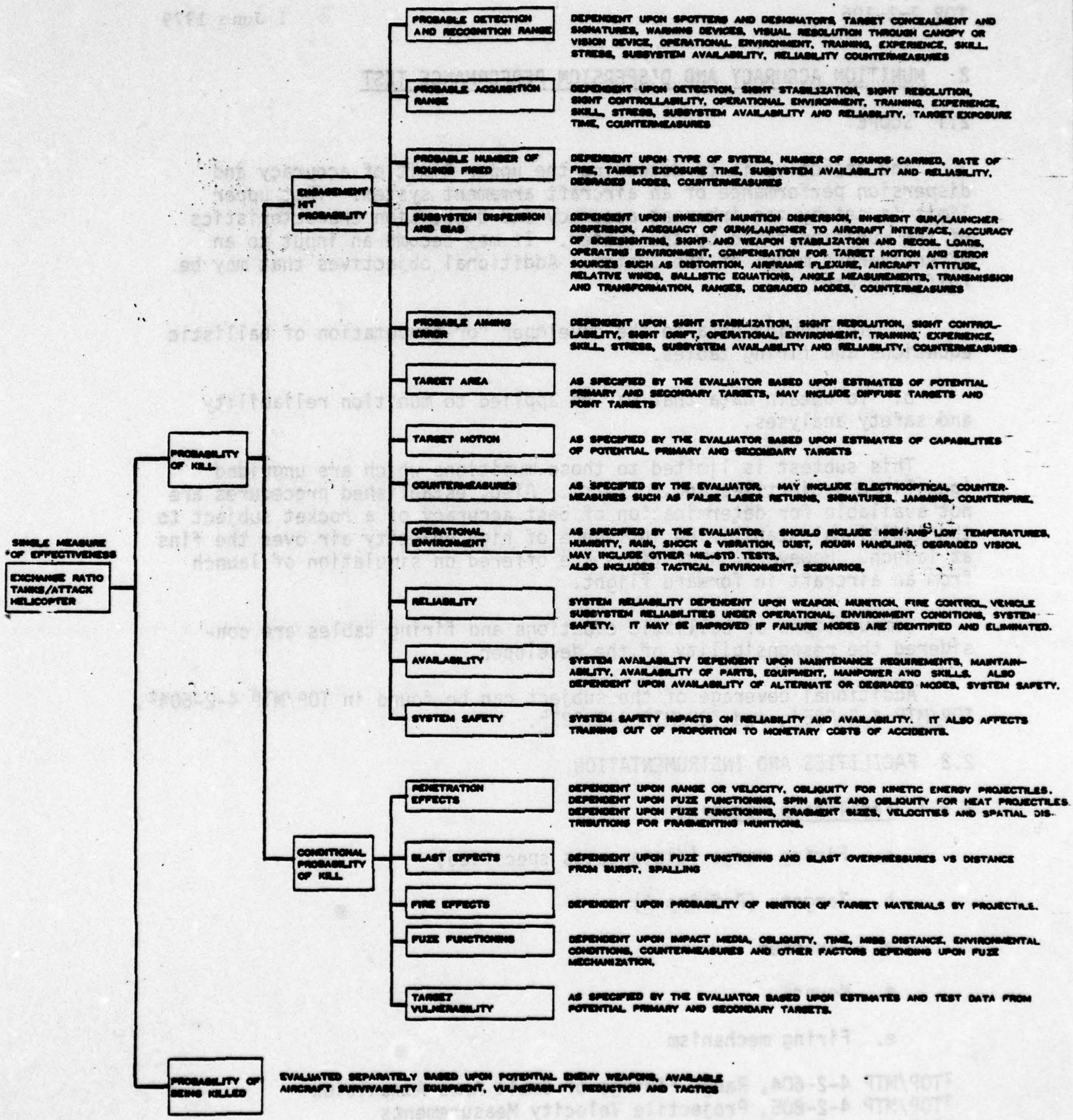


FIGURE 1-1. TEST DATA REQUIREMENTS AS IDENTIFIED BY WORKING BACKWARD FROM A MEASURE OF EFFECTIVENESS

2. MUNITION ACCURACY AND DISPERSION PERFORMANCE TEST

2.1 SCOPE

The objective is to determine the upper limit of accuracy and dispersion performance of an aircraft armament system. That upper limit is set by the inherent accuracy and dispersion characteristics of the munition fired by the system. It may become an input to an effectiveness model of the system. Additional objectives that may be fulfilled are:

a. To provide data to the developer for computation of ballistic equations and firing tables.

b. To obtain data that may be applied to munition reliability and safety analyses.

This subtest is limited to those munitions which are unguided (gun-fired projectiles and rockets). Also, established procedures are not available for determination of best accuracy of a rocket subject to the additional stabilizing influence of high velocity air over the fins at launch. However, suggestions are offered on simulation of launch from an aircraft in forward flight.

Computations of ballistic equations and firing tables are considered the responsibility of the developer.

Additional coverage of the subject can be found in TOP/MTP 4-2-604[2], TOP/MTP 4-2-805[3], and TOP/MTP 4-2-827[4].

2.2 FACILITIES AND INSTRUMENTATION

2.2.1 Facilities Required

a. Firing range (distance as specified)

b. Targets (Ref App A)

c. Launcher

d. Mount

e. Firing mechanism

[2]TOP/MTP 4-2-604, Range Firings of Small Arms Ammunition
[3]TOP/MTP 4-2-805, Projectile Velocity Measurements
[4]TOP/MTP 4-2-827, Time of Flight and Ballistic Coefficients

2.2.2 Instrumentation

The following items may be required for aircraft armament munition accuracy and dispersion and related tests:

a. Boresight with adaptor

b. Gunner's quadrant

c. Ballistic chronograph

d. Projectile sensing (lumiline) screens

e. Chain (tape measure)

f. Meteorological instruments

g. Transits

h. High-speed motion picture camera or video camera and recorder

i. Chamber pressure transducer/recorder

j. Doppler radar velocimeter

k. Space position instrumentation (radar, cinetheodolites or radar tracker, depending upon the accuracy desired)

2.3 PREPARATION FOR TEST

2.3.1 Preparation of Data Required

The test planner should determine, through consultation with the evaluator, the developer and the data analyst, the information each requires. This includes the accuracy or confidence required in the final result as that will affect the instrumentation selected and sample sizes used. The end use of the data (effectiveness, range tables, etc) should also be learned. A check list of test conditions and data that may be obtained during or incidental to the munition accuracy and dispersion test includes:

a. Specified ranges

b. Specified target, horizontal or vertical

c. Specified and actual launcher characteristics (wear or remaining life, rate of twist, length)

d. Number of launchers, serial numbers

e. Limiting and actual meteorological conditions; winds, temperature, air density

f. Specified and actual munition temperature

g. Specified control ammunition

h. Quadrant elevation of launcher boresighted on the target (0 superelevation)

i. Quadrant elevation of launcher with superelevation

j. Azimuth of line-of-fire

k. Impact coordinates

l. Instrumental velocity near the muzzle

m. Continuous velocity (velocimeter or laser tracker)

n. Time of flight

o. Tip-off angle (rockets)

p. Yaw

q. Drift

r. Chamber pressure

s. Reliability

Not all of the above data items can be obtained during the same firing but may be obtained in a sequence of firing with minor changes in setup. Only the accuracy, dispersion and reliability data are likely to be of interest to the evaluator. The developer may be interested in the other quantities listed.

2.3.2 Preparation of Facilities

Munition accuracy and dispersion test facility preparation will include:

a. Range Siting. A firing range should be selected with consideration being given such factors as safety requirements, potential interference, target characteristics, distances required, relative elevations, prevailing winds, availability and accessibility of instrumentation, and temperature conditioning chambers.

b. Targets. See Appendix A. A value analysis should be conducted considering the economics of moving the launcher or the target or of constructing multiple stationary targets to achieve specified distances. The result may be so obvious that a formal analysis is not required.

Communications facilities are essential if personnel are downrange in the vicinity of the target during firing. Wire will have to be installed if telephones are used.

2.3.3 Preparation of Equipment

The launcher (Mann barrel or rocket launcher) may be unique to the test item. If so, the developer will generally provide one or more launchers for the test. There is little standardization among launchers; consequently, some design and metalworking may be required to adapt the new launcher to existing mounts. The launchers should be measured with a stargage to determine actual internal diameters throughout the length. A borescope is used for visual inspection of the internal condition of the launcher. The rate of twist of Mann barrel rifling should be measured. If Mann barrel chamber pressures are required, the barrel must be drilled for the gage.

Percussion primed cartridges will normally be fired from a Mann barrel with a lanyard. Electric primed cartridges and rockets are fired using an electric firing box with safety provisions to ground the firing circuit and interrupt power during loading.

Best rocket accuracy and dispersion will be difficult to determine in ground firing if the launch velocity is low and the rocket gradually accelerates after launch. During the low velocity launch the rocket is subject to greater disturbance effects with little aerodynamic stabilization from fins. Some success has been achieved in improving rocket accuracy and dispersion with special launchers such as described in the following paragraph.

A long-tube launcher will guide the rocket until a higher exit velocity is attained. If the long-tube launcher is mounted on bearings and spun during launch it will tend to increase the stability of the

rocket. Special launchers have not been fully developed and some experimentation may be required to obtain optimum results. Moreover, the objectives of the test must be carefully considered to assure that this equipment does not compromise fuze functioning or other data.

The mount employed for single-shot munition accuracy and dispersion testing should be sufficiently massive and rigid to prevent significant angular motion while the projectile is in the launcher. The mount should also be accurately and quickly adjustable for azimuth and elevation. The "Frankford Arsenal-type" (FA) machine rest satisfies these requirements for most Mann barrel fired cartridges. A functional recoil mechanism should be used for cartridges larger than rifle caliber for optimum accuracy.

A howitzer carriage or tank gun may be adapted for use as a mount in lieu of a FA rest.

Temperature conditioning chambers for munitions should be adjacent to the firing position to avoid excessive temperature change. If possible, the weapon and munition will be conditioned together and fired from the chamber at the specified temperature.

Equipment required for target scoring and repair should be made readily accessible.

2.3.4 Preparation of Instrumentation

Selection and preparation of instrumentation for the munition accuracy and dispersion test will depend greatly upon the data requirements.

Instruments for laying the launcher will generally consist of a gunner's quadrant and a boresight. The boresight may require fabrication of a bore adaptor if the boresight kit does not contain one for the test caliber. Alternatively, a sight adaptor may be used entirely external to the bore to avoid the risk of inadvertently shooting the boresight out.

The external sight may rest on V-blocks over the barrel.

Vertical target scoring instruments will consist of measuring tapes or chains or cameras. Little preparation other than maintenance and calibration is required. Horizontal target scoring will require installation of motion picture or video camera in a helicopter for overhead photography of the targets.

Velocity instrumentation will consist of counter chronographs and projectile sensors such as lumiline screens, sky screens, coils, or make or break screens. Preparation will require accurate positioning and measurement of projectile sensing screens. Lumiline screens may require shielding from ambient light.

The Precision Aircraft Tracking System (PATS) laser tracker is the preferred instrumentation for rocket velocity measurement over the flight of the rocket if retroreflectors can be fitted to the rocket. Position and velocity data are obtained by the PATS. Site preparation (concrete pad, power, and communications) is required for the PATS if relocation is necessary.

Doppler radar for velocity measurement requires little site preparation other than electric power. The firing event should be recorded by connecting the velocimeter to a pick-up on the launcher or firing circuit.

If chamber pressures are required, the recommended pressure transducer should be fitted to the barrel. Obtain or fabricate a fixture to accurately drill the cartridge cases used for pressure firings.

2.4 TEST CONTROLS

As a minimum the following steps should be taken to assure accurate and complete results:

a. Review the data requirements of the evaluator, developer and data analyst to be sure thay have been accommodated.

b. Check the test items and control rounds to assure that the correct types and lot numbers are on hand, in good condition and not under suspension.

c. Perform a sensitivity analysis using hypothetical test data and the intended analytical plan. From the sensitivity analysis determine the required accuracy of data which will provide adequate final results.

d. Determine the consequences of one or more lost data points and provide alternative means to collect or analyze the data to minimize the impact of the lost data.

e. Ask the hypothetical question: "How much confidence do we need to have that the data are truly representative of what we claim?" Then devise statistical means of answering the question.

f. Check all instruments used for current calibration.

g. Check launchers and mounts for condition, tightness, serviceability, and provision for recoil.

h. Use more than one launcher and compare results from each.

i. Minimize time from removal of round from temperature conditioning chamber to firing.

j. Provide sufficient time for test items to stabilize at the specified conditioning temperature.

k. Measure winds at midrange and aloft during accuracy and dispersion fire at long ranges.

l. Insure that distances between corresponding corners of velocity screens are equal to within 0.1 percent of the distance between screens.

m. Insure that photoelectric screens are sufficiently far from the muzzle of Mann barrels or protected to avoid triggering on muzzle blast.

n. Establish a uniform firing cadence to avoid nonuniform heating and cooling of Mann barrels.

o. Avoid firing at long ranges if winds are excessive or gusty.

p. Spot each round impact to correlate with individual velocities.

q. Fire sufficient rounds per target to approach a normal distribution. Although generally used in the past, 10-round groups may not be sufficient for determining normal distribution.

r. Determine the cause of significant correlation in impact coordinates as indicated by an elliptical dispersion pattern with major and minor axes which do not fall on the horizontal and vertical axes.

2.5 METHOD AND DATA REQUIRED

2.5.1 Method

a. Place target, launcher, bombproofs, meteorological instrumentation and ballistic instrumentation in appropriate relative positions.

b. For large horizontal targets position helicopter with scoring camera over the target.

c. Fire several non-test rounds to adjust impact on the target and to establish uniform round-to-round conditions.

d. Fire the specified number of rounds per target in accordance with the test plan.

2.5.2 Data Required

a. Model and lot numbers of munitions used including major components (fuzes, warheads, etc)

b. Serial numbers of launchers used

c. Stargage and inspection records

d. Launcher elevation and superelevation

e. Line-of-fire (azimuth)

f. Target impact coordinates (by round number)

g. Aiming point relative to target

h. Meteorological data, perferably at midrange, wind velocity and direction, dry bulb and wet bulb temperatures, barometric pressure

i. Velocity (by round number)

j. Observation of functioning

k. Observation of misses (high or low, left or right)

l. Chamber pressure (if required)

2.6 DATA REDUCTION AND PRESENTATION

Round-by-round impact coordinates correlated with velocity should be presented in tabular form. Impact coordinates should also be plotted on a graphical representation of the target.

Coordinates of centers of impact (average x, y) should be tabulated and indicated on plotted targets.

Compute the standard deviations of impacts for each coordinate, tabulate and present with target plots. One or more missed rounds may be handled by estimating the parameters for an assumed normal distribution using the method of maximum likelihood for truncated samples. Any information about the region of miss should be recorded.

3. SYSTEM ACCURACY AND DISPERSION TEST

3.1 SCOPE

The objective of the system accuracy and dispersion test is to obtain data for computation of hit probability. Hit probability (single shot hit probability, first round hit probability, N round hit probability or engagement hit probability) is a key measure of effectiveness for evaluation of the performance of aircraft armament systems.

The developer may require additional component data which are not essential to a go-no-go type evaluation of the system but may be essential to further development of the system. This information will enhance the system evaluation.

The first general approach to aerial accuracy and dispersion tests is the binomial method. The numbers of hits and misses on a target are recorded and used to compute the reliability of hitting at various levels of confidence. This hit or miss method is the simplest but yields the least information since bias and dispersion information is not obtained and results include the gunner performance. A larger number of rounds may have to be fired, therefore, to compensate for the reduced data obtained and to evaluate the gunner performance.

The second general approach to aerial accuracy and dispersion tests is to measure impact coordinates for computation of bias and dispersion. If required, error sources will be instrumented and measured. The data acquired from the instrumentation will be reduced using the fire control equations furnished by the developer. An attempt will be made to correlate error sources with bias and dispersion.

Actual computation of hit probability will normally be the responsibility of the evaluator. Some theory and techniques for computation of hit probability by the test agency are provided in Appendix B for use as a form of test control.

This procedure is limited in that the developer must provide the ballistic equations that are implemented in the fire control system. The procedure pertains most directly to flexible-gun-type systems since these are probably subject to more error sources than other types of systems. The procedures require slight modification for fixed guns and rockets. Greater modification is required for guided missile systems. A block diagram illustrating the major components of the system to be evaluated should make apparent the modifications necessary.

3.2 FACILITIES AND INSTRUMENTATION

3.2.1 Facilities Required

Instrumented firing range

Targets and markers

Landing, rearming pads

Meteorological towers

3.2.2 Instrumentation

Space position measurement system

On-board multichannel recorder

System voltage taps

Analog (FM-FM) telemetry transmitter

Analog (FM-FM) telemetry receiver, recorder

Digital (PCM) telemetry transmitter

Digital (PCM) telemetry receiver, recorder

On-board signal conditioning

Analog to digital converters

Multiplexers

Synchro/resolver to digital converters

Displacement transducers

Velocity transducers

Accelerometers

Strain gages

Load cells

Thermocouples

Vertical gyro

Rate gyros

Aiming error detector

Video cameras, transmitters

Motion picture cameras

Relative wind sensors

Instrumentation pod

Time code generator

Data reduction computer system

3.3 PREPARATION FOR TEST

3.3.1 Identification of Data Required

Review the test design plan prepared by the evaluator. Determine whether or not the evaluator or developer requires a fire control analysis.

Assuming a fire control analysis is required, prepare a block diagram of the system. Identify system inputs and outputs including potential error sources not compensated for.

3.3.2 Identification of Error Sources

3.3.2.1 General:

The errors associated with a fire control system can be classified as either: target position error, computational error, or the error associated with the positioning of the weapon and the uncorrected external effects on the ballistic trajectory.

Typical errors associated with the input of a fire control system involve such things as target and platform motion, and range determination. Examples of errors associated with the output include ammunition variation, gun tube vibrations, and weapon positioning. The input and output errors are relatively fixed in comparison with those of the computational type. Computational errors are more variable in that they are dependent on the particular circumstances under which firing takes place.

A sample functional block diagram of a fire control system showing the basic components is shown in Figure 3-1. Included in this diagram are the basic fire control functions of target location and tracking, computation, and weapon positioning. Within these component blocks are sources of error which contribute to the overall error associated with each component and also to the total error in the system. The sources which produce each individual component error will now be described and the contribution of these errors to the overall bias and dispersion of the measured shot distribution will be considered.

3.3.2.2 Specific:

a. Target Position

The first source of error in the fire control system is the difference between the observed target location (x_o', y_o', z_o') and actual target location (x', y', z') with respect to the location of the weapon (x, y, z). If the weapon is assumed to have the coordinates (o, o, o), the target location may be specified as ϕ mils elevation, θ mils azimuth, and R meters slant range. Errors in target position are represented by ϕ_e, θ_e, and R_e. In an otherwise perfect system these errors cause the weapon to be aimed at the point ($\phi + \phi_e$, $\theta + \theta_e$, $R + R_e$) rather than the point (ϕ, θ, R) which would produce a hit on the target. Target position errors are due to the target observation system and are caused by the following:

(1) Insufficient angular resolution in the target sensor.

(2) Inaccuracy in the target ranging system.

(3) Inaccuracy in referencing the observation point (observation platform not level or otherwise incorrectly oriented, backlash, mechanical eccentricities).

Errors in the vertical (ϕ) will cause the weapon to fire at points above or below the target, depending upon the sign of the error ϕ_e. Errors in the horizontal (θ) cause the weapon to fire to the left or right of the target, depending on the sign of the error θ_e. Errors in the distance (R) generate errors in the ballistic computations of gravity drop and time of flight of the projectile which add to the ϕ_e component. Range error (R_e) effects will be discussed later in more detail.

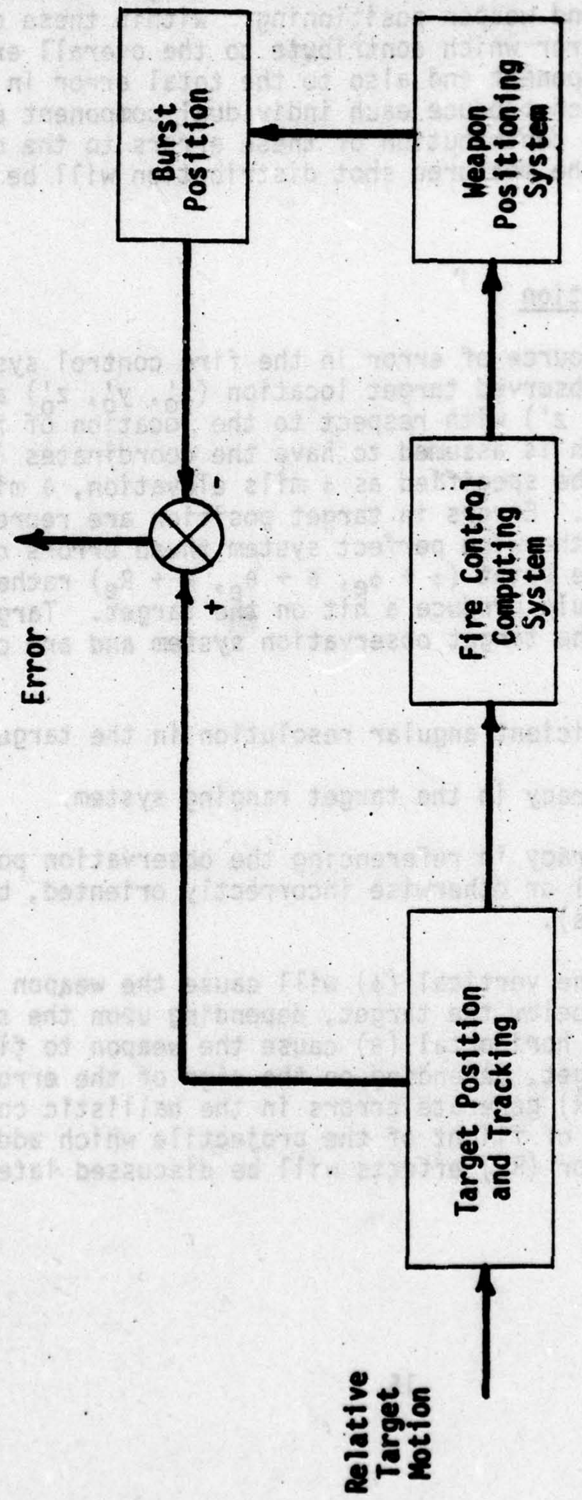


FIGURE 3-1. Functional Block Diagram of Fire Control System

b. Target Motion

The effect of a moving target is to make the position coordinates (ϕ, θ, R) vary with time. These introduce additional errors such as the inability to track the target at the correct angular rate and a time lag due to the response time of the weapon servo system.

c. Range Estimation

Error in estimating the true range of a target will significantly affect the point of impact of the projectile. This error ranges from a minimum for an automatic ranging device (pulsed LASER), to larger values for less accurate range finding devices (stadia, optical range finders), to finally the least accurate; manual range estimating. Inaccuracies on the order of $\pm$100% of the true range to the target are common in the latter case.

The normally accurate LASER range finder may give erratic results during low level operation if returns are received from foliage or when small angular perturbations result in large range changes at low incidence angles.

Furthermore, there will be an error resulting from the time lapse during movement by the target and/or vehicle from the time a range is selected to the time the burst is impacted in the target zone. As an example, consider an aircraft at a given altitude, moving at a constant speed of 167 kph, and firing at a target, which is moving in the same direction along the ground at a speed of 72 kph. The error in range resulting from a $\pm$1 second time interval from ranging to firing is 27 meters. Also, if time of flight of the rounds to the target is 3 seconds, the target has moved another 60 meters during this interval. Compensation for this error should be included in the equations for relative motion used in the weapon offset angle computations.

d. Weapon Offset Angle Computation (Lead Angle)

Lead angle error is the angle between the lead angle produced by the system and the required lead angle to hit a target. The lead angle itself compensates for the effect of a moving target and/or weapon platform and the error depends on various factors. Some of the more significant types of factors leading to errors in lead angle computation are summarized in the following paragraphs:

(1) Errors in the Digital Computer. This pertains to the loss of data bits due to errors in the logic and storage circuits. Depending on the significance of the digit in which the loss occurred, this could have a profound effect on the fire control solution.

(2) Errors in Analog Computers. This pertains to a loss in accuracy due to deterioration of components initially and during use. The wear in bearings and contacts, and the change in characteristics with age of transistors, integrated circuits, resistors, inductors, and capacitors must be considered in this type of error.

(3) Errors in Electronic Circuitry. These errors include the following:

(a) Deterioration of components caused by aging.

(b) Amplifier drift caused by temperature and supply voltage variation.

(c) Power supply regulation deficiency.

(d) Phase shift in the signal voltages.

(e) Potentiometer winding defects.

(4) Mechanical Elements. Errors result from loose bearings or inaccurate gear cuttings, hysteresis in springs, and eccentricities in bearings, shafts, cams, etc. Vibration can cause dynamic error in the accelerations on linkages and cams which must follow rapidly changing signals.

e. Sighting Accuracy

This is the capability of the sighting system to correctly define the point of aim. Error sources include the following:

(1) Gunner Proficiency. This is the error due to the gunner being unable to lay the sighting reticle exactly on the target center. This error is a function of gunner training, gunner experience, and tracking equipment capability.

(2) Equipment Errors. These are errors caused by such things as misalignment between the gun and the sight and the inability of the gun to remain fixed on a target when the helicopter is subjected to erratic angular inputs, e.g. during firing and flying through turbulent air.

(3) Boresight Error. This is the residue or error remaining after sight - gun alignment and the nonretention of alignment as a result of temperature changes, firing shock, and aircraft maneuvering. The purpose of boresighting is to make sure that the weapon line of fire and the sight line are in the correct alignment with the system references. The ability of a system to hold this alignment specifies the magnitude of an error (bias and dispersion) to be considered in the calculation of hit probability.

(4) Parallax Error. This is the bias error which results from the sight and the gun being physically mounted at separate positions in the vehicle. In some systems, boresignting and zeroing are used to converge the line of sight and the line of fire to a target at a specific range. At any other range, however, the displacement between sight and gun causes a parallax error to occur.

In systems where parallax corrections are computed at different ranges, the bias error cannot be separated from other portions of the overall computation. Thus, parallax is not considered a separate error source in the hit probability calculation but is included in computer computation error.

f. Ammunition Variations and Ballistic Effects

Errors caused by projectile variations, i.e. differences in ammunition due to such things as propellant loading, temperature, and lot-to-lot variations in projectile size, shape and weight, and projectile center of gravity, result in different ballistic trajectories for different rounds.

When the propellant temperature varies, a change in muzzle velocity occurs. The functional relationship is a direct one, i.e. a higher temperature results in a higher muzzle velocity. The effect causes the round impacts to be inaccurate, and can be significant.

Projectile drift is the lateral deviation of the projectile from its plane of departure such that the horizontal trace of the trajectory is a curved, rather than a straight line. It is caused by certain aerodynamic effects. The most significant of these is gyroscopic precession of the projectile along the axis horizontal to the line of fire. It is induced by projectile spin and the force exerted by the air along the spin axis which causes the projectile to precess in a direction perpendicular to the applied force and the direction of spin. A second source is the magnus effect, producing a difference in air pressure over the projectile body thus causing drift. A third source,

the cushioning effect, results in a rolling movement of the projectile due to the air piled up on its underside. The effects of these last two sources are minor in comparison with the first.

Rockets are extremely susceptible to errors caused by g-loads and aerodynamic effects at the time of launch. Aircraft slip and rotor downwash will create side loads on the unsupported portion of the rocket as it emerges from the launcher.

g. Airframe Distortion

As a result of firing, movement of the rotor blades, and other concentrations of stress within the aircraft, severe shock and vibration can occur. The resultant distortion affects both the sight - weapon alignment and the parallax correction. Under certain conditions airframe distortion may be the most significant factor in accuracy degradation of the fire control system.

h. Atmospheric Compensation Errors

These errors include the effects of wind and static air resistance which influence the predicted trajectory of the projectile.

The static air resistance is a drag component on projectile motion which varies as a function of temperature, density of the air, and altitude. It is derived from measurements of the temperature of the air and both the static and dynamic pressure. Inaccurate air resistance corrections applied by the computer have the effect of significantly influencing the predicted projectile trajectory.

Inaccuracies in the measurement of the velocity and direction of the winds result in the erroneous compensation for the effects of wind. The crosswind effect is time varying, occurring over a specific interval of time, and must be compensated for only within that period. Corrections applied when there is no wind will likewise introduce error.

The tail wind blows in the direction of the plane of fire. It has the effect of producing less drag on the projectile by reducing its velocity relative to the air, causing it to encounter less air resistance.

The head wind directly opposes the forward motion of the projectile, increasing its velocity relative to the air, and increasing drag.

i. Computer Errors

The ballistic equations and equations of motion programmed on the fire control computer are an approximation of the exact solution of the fire control problem. Hence, their validity will depend on how

well this real-world situation has been approximated and will vary with various factors, e.g. range, aspect angle, etc. Some of the significant computer errors associated with this approximation are summarized below:

(1) Digital Computer Errors. Roundoff error results when the computer must round a number off to the machine word length, i.e. the number of bits or significant digits that the computer is limited to. These errors accumulate and become significant as the number of calculations involved gets large.

Truncation errors, e.g. in the ballistic equations and equations of motion, result from continuous data being approximated by a series of stepwise values stored in the computer, or by the computation in a subroutine of a series approximation to the function. Since the computations require as few terms as possible to be retained in the series, the errors caused by truncating the series is the truncation error. This error may be minimized by increasing the sampling rate of the input data or by increasing the number of terms in the series.

Real-time operation refers to the accomplishment of the fire control solution in an interval of time fast enough such that the solution may be considered to be instantaneous, i.e. the fire control parameters do not change significantly during the time interval required to compute the solution. The computer must operate in real time to be effective, even if this results in a decrease in accuracy. Inaccuracies in the data are magnified by the computer, when the solution time is long enough to permit significant changes in the data between solution updating.

Certain functions, such as a sine or cosine function, used to carry out coordinate transformations, are required often enough that they are either stored as tables or calculated by a computer subroutine. These values are necessarily approximations and provide a source of error.

The information signal at the input to the fire control computer is sampled at a rate (called the Nyquist rate) at least twice the highest frequency of interest. This allows reconstruction of the original waveform, or, a minimization of the data loss between sampling intervals. An input frequency above 1/2 the sampling frequency, manifests itself as an error in the fundamental frequency components of the input signal. If high frequency signals are necessary to be sampled, a high-speed computer is required. Since this is expensive, a compromise is usually made between minimizing the sampling error and reducing the size and complexity of the computer.

(2) Analog Computer Errors. There are three types of analog computers: mechanical, electrical, and electromechanical. Errors in an analog computer which are of a static nature are the linearity errors of potentiometers, the null and transformation errors of synchros and resolvers, the drift and nonlinearity of amplifiers, mechanical irregularities (cams, differentials, etc), and the zero offset errors of components.

Analog computers depend heavily on potentiometric devices to perform arithmetic functions and synchros and resolvers for trigonometric functions. Changes in reference voltage and wear on potentiometer windings are sources of inaccuracy. Shaft and bearing eccentricities and imprecision in the physical location of the windings are sources of error in the synchronous transformer devices.

Most analog solutions are position (angle or distance) related in the computing elements (shaft angle, gear and cam rotation, etc). Solution accuracy is related to manufacturing precision and servo response.

Dynamic bias errors concern the time lag in response of the system and depend directly on the bandwidth; a larger bandwidth implying a more rapid response time. Since the response of the computer is equivalent to the response of the element driving it, dynamic bias errors are associated with the bandwidth limitations of the servos and gyros.

Since most analog computers operate in series, i.e. one servo drives another, the total response time is the sum of the response times of all servos in the series.

Noise errors are associated with the tracking device or with such sources as potentiometer contact noise, gear backlash and tooth errors, and stray voltage pickup. To minimize the noise, servo and gyro bandwidths should be made as small as possible, a measure which will serve to increase dynamic bias errors. Therefore, a compromise is necessary to determine a bandwidth which will yield the best overall result for the system in terms of these error sources.

(3) Aircraft and Turret Motion Compensation Errors. Other conditions which the computer is normally expected to compensate for are errors caused by maneuvering of the aircraft.

An angular rate error results from angular rotation of the aircraft and/or turret at the time of firing.

The movement of the firing platform imparts horizontal and vertical velocity components to the projectile which are both time and angle dependent. The error is a maximum when the gun is positioned at right angles to the motion and decreases as the angle between the gun and direction of motion decreases.

Under rough flight conditions, the vehicle is subject to erratic angular inputs which tend to pull the gun away from the target. The ability of a system to compensate for the effect and to keep the gun pointed at the target under these conditions is a measure of stabilization.

j. Weapon Servo Error

These errors result from the inability of the turret servos to precisely follow the command signals in both rate and position. The error tracking rate capability is dependent on the acceleration in the forcing function while the null position error is fixed to electrical sensitivity and mechanical irregularities such as eccentricities, inexact gear ratios, etc.

Servo lag is the error in response time resulting from the weapon positioning signal lagging the input tracking signal. It may be compensated for by achieving greater sensor sensitivity in the analog systems and using a higher data sampling rate in the digital systems.

Servo response is the measure of the capability of the servo to maintain the weapon in the correct relationship to the sight under changing sight line and loading conditions. The sight line changes as a function of vehicle and target motion. Loading changes are caused by firing shock, air drag on the weapon, and airframe vibrations transmitted to the weapon. System stability may be enhanced by providing feedback in response to the resultant accelerations.

3.3.3 Preparation of Facilities

Firing range targets and markers should be surveyed in at positions appropriate to the expected accuracy and dispersion of the system.

3.3.4 Preparation of Equipment and Instrumentation

Application of instrumentation to the fire control system will be one of the major tasks of the system accuracy and dispersion test. Because of the very limited available volume within an attack helicopter some compromise will probably have to be made in locating the bulkier

instrumentation components. Generally, instrumentation space will be appropriated from the internal ammunition compartment for tests involving wing store weapons such as rockets, missiles and podded guns. On the other hand, for tests requiring the design use of the ammunition compartment, instruments may be mounted in a wing store pod.

The instrument package or pod should be designed to contain the major portions of each on-board instrumentation system employed. These will include analog signal conditioning circuits, resolver and synchro to digital converters, time division multiplexing circuits and pulse code modulation (PCM) encoders, frequency modulation and multiplexing (FM-FM) modules, magnetic tape recorder, telemetry transmitters, range time receiver, video transmitter, gyro package and special fire control system interface adapters.

The PCM system has the advantages of superior accuracy and a greater number of channels than the FM-FM system. However, since each channel may be sampled only a few times per second the frequency response is low compared to FM-FM. Therefore, the FM-FM is used for data from accelerometers and similar signals with frequency components of a kilohertz or more. PCM is used for slowly varying signals or where greater accuracy is required at the expense of using several channels for one signal.

Transducers will generally be located remotely from the pod and connected to it by cables. Transducers may be installed by the test agency but in some cases the transducer will be a part of the fire control system. For example, the tester cannot hope to add on more accurate angle measuring transducers than the synchros and resolvers (with anti backlash gears) that may be a part of the fire control system. In these cases the developer must be assured that the instrumentation voltage taps do not load the test item nor introduce spurious signals. This may be achieved by specifying that all voltage taps of signal lines be connected to a high input impedence voltage follower amplifier immediately adjacent to the tap. The effectiveness of this measure can sometimes be checked by observing for any boresight shift as the tap is connected and removed.

A different problem may present itself in recording digital data words from a fire control computer. Because of the differing clock rates of the fire control and PCM systems, it is likely that an interface buffer will have to be designed and constructed.

Angle measurements in an airborne environment can probably be made most accurately with synchros or resolvers. These are described in Appendix E.

Synchro and resolver to digital converters available in module and bench instrument form may be interfaced to the sight, turret, gyro, and angle of attack sensors. Separate tracking converters can be used for each channel or a single sampling converter may be used with time division multiplexing of the analog signal. The bench instrument may be used in static tests, the modular converters in airborne tests. Aiming error instrumentation will depend upon characteristics of the sight used. The preferred technique for large stabilized sights with provision for a gun camera is to replace the gun camera with a video camera. The video signal is transmitted and recorded. A video camera may also be used with fixed sights if mounted and boresighted parallel to the line of sight.

Lightweight sighting systems such as helmet sights cannot bear the weight of a full size camera. These may be instrumented with miniature video cameras or the YPG Aiming Error Detector. The aiming error detector is a lightweight electrooptical device used to sense the angular excursion of a flashing light source in the field of view. The dc signal outputs are proportional to the off-axis angles about two axes. A high intensity xenon flash lamp (200 pulses/second) light source in the vicinity of the target is required for use with the aiming error detector. It should be protected during firing and the light reflected from an expendable mirror.

Rate gyros should be mounted on the weapon and the airframe if the effectiveness of stabilization is to be determined.

Retroreflectors consisting of mirrors in the configuration of the corner of a cube are mounted on the aircraft or missile to be tracked. The corner cube reflectors have the property of reflecting the LASER beam from the Precision Aircraft Tracking System (PATS) upon itself.

Angle of attack sensors should be mounted in areas that are not subject to excessive turbulence. That is not always easy and some experimentation may be required to find the best location for a particular aircraft.

Miniaturization is essential for airborne instrumentation. This applies equally to transducers, connectors and cable, and the data conversion, recording and telemetry equipment.

Any instrumentation installation should be inspected by the aircraft maintenance officer or technical inspector. He will determine whether a safety of flight release is required.

3.4 TEST CONTROLS

The planned analysis should be carried out using simulated data prior to the start of testing to assure that the approach is workable. Then a sensitivity analysis in which the effect of small input perturbations is observed in the analytical output should be conducted. Required accuracy and precision of measurements can be inferred from the sensitivity analysis. Therefore, instrumentation accuracy values are not set forth in the TOP. Moreover, the consequences of lost data can be observed in the sensitivity analysis and steps may be taken to safeguard against loss of essential data.

Data should be reduced as soon after recording as possible in order to check for anomalies that should be corrected in future runs.

All instruments including the fire control instruments should be calibrated, either by the calibration laboratory or by the user.

The sense of angle rotations to be used in transformation matrices should be checked for consistency.

The requirements of the evaluator and the developer should be double-checked, preferrably by providing a sample of results for approval using simulated data as early as possible in the test.

3.5 STATIC TEST METHOD AND DATA REQUIRED

3.5.1 Method

The static tests identify the individual error sources and the magnitude of their contributions to the component error. The individual errors combine either arithmetically or algebraically to produce the quantity commonly referred to as the residual component error. The accuracy of the data transmitted by the component is limited by the residual component error. All of the error sources can be identified but it is not always possible nor is it necessary to isolate and define the magnitude of each. It is accepted practice to identify and determine the magnitude of each more troublesome error sources. The most common test procedures are identified in the following paragraphs:

a. Boresight. This procedure aligns the aircraft, the sighting system, and the weapon to the reference system, usually the datum line of the aircraft. In the more complex systems, the procedure also includes harmonization. Boresighting is generally defined as the

mechanical procedure for adjusting the weapon to cause the projectile to impact at the point of aim when the point of aim is in coincidence with or parallel to the datum or reference line. Under these conditions the boresight procedure accounts for the physical displacement (parallax) between the sight and the weapon and the firing reaction of the weapon. The procedure requires the use of a target system with reference points for the datum line, the sight line, and the bore line. Detailed procedures vary from system to system. The detailed procedures should contain instructions for the construction of the target, the positioning of target and aircraft, and the adjustment routines. If the displacement between the sighting station and the weapon station is large ($\geq$1 meter), it will be necessary to apply additional corrections for parallax at sighting angles offset from the reference line if the basic accuracy of the system is to be maintained at other than the reference position.

Sight-bore tracking is determined by placing targets at small (5° to 10°) intervals throughout the limits of travel, laying the sight and reading the sight-bore displacement from the boresight. In the rudimentary systems, comparison of the boresight readings with the bore alignment values directly yields the sight-bore tracking error. In systems which compute and apply parallax and ballistics corrections to the weapon positioning system, it may be necessary to apply additional correction factors to determine the actual sight-bore tracking error. Additionally, when laying the sight to the target, the sight should approach the target from one direction. If the sight overshoots the target, the sight laying should be restarted from a position beyond the target in the original direction. This procedure is necessary because it causes any errors due to backlash or system error sensitivity to appear as a constant magnitude directional bias in the data. The direction of the bias reverses when the direction of the motion reverses. Biases contributed by other sources are characteristically constant in direction.

Harmonization or alignment is generally defined as that procedure which nulls, initializes, and synchronizes the system. It includes and expands the boresight procedure to include the adjustment of sensors, resolvers, transducers, biases, references levels, etc, to align the total system to the initial reference. The angle transmission signals from sight to weapons should also be measured. If the signals are from standard synchros or resolvers a synchro/resolver to digital converter may be used for maximum accuracy and resolution. Digital signals may be recorded and converted to engineering units.

If the sight looks through the aircraft canopy, it must be calibrated without the canopy.

b. Backlash. Backlash is by definition the failure of the mechanical components to return to the original neutral position upon the release of applied force. Backlash occurs generally in the rotational components and is the direct measure of "play" or slack in the meshing of gear tooth surfaces and between gear hubs and shafts. Backlash is measured by attaching a displacement gage to a nonmoving part of the structure in a position which allows the displacement sensing element to contact the moving element in one plane (e.g. horizontal or vertical). A force insufficient to overcome system inertia is applied to the moveable element in one direction in the selected plane and released. The gage is nulled. The force is then applied in the reverse direction and released. The residual displacement is backlash in the plane.

c. Line of Sight Angular Resolution. This procedure determines the undetected angular error in the position of the target as defined by the target detection system. To determine this error a target is positioned near the maximum range of the detection system, and the detection system is aligned to the aiming point on the target. The target is then moved until an error is observed in the relative positions of the sight-line axis and the aiming point on the target. The angular error is the ratio of the target linear displacement to the target range in kilometers (D/R = mils).

d. Ranging Accuracy. This procedure determines the inherent accuracy of the ranging system. To accomplish the test, it is necessary to construct a surveyed range with target positions at discrete distances from the sighting point to the maximum range of the system. The range to each target location as determined by the system is compared with the surveyed range to determine the ranging error. In manual ranging systems the error characteristic is usually system- and operator-dependent and may exhibit a directional bias or be random. In automated systems the error will usually be directionally biased or cyclic.

e. Range Resolution. This procedure determines the error sensitivity of the ranging system. An initial range measurement is made to a target. The target is then moved through a radial distance until the range indicated by the system changes in the least significant digit. The distance through which the target is required to move to produce a change in range in the system is the system range resolution.

f. Evaluation of the Equations. To evaluate the system fire control equations it is necessary to compare problem solutions generated by the system equations with solutions to the same problems generated by the most precise equations for ballistics effects and motion compensation. To accomplish this, an off-line computer is required to:

(1) Synthesize the target to flight path geometry, target motion, meteorological data, and platform motion data as used by the system fire control.

(2) Solve the system fire control equations using the synthetic data inputs.

(3) Synthesize the target to flight path geometry, target motion, meteorological data, and platform motion data required for the theoretically correct prediction equations.

(4) Solve the theoretically correct equations using the synthetic data inputs.

(5) Develop the errors in the system fire control equations by comparing the two sets of solutions.

The errors resulting from this exercise, when analyzed, show the inherent accuracy of the fire control equations. If the errors are graphically displayed as functions of range to, range rate of change, and angular velocity about the target, the range of effective operating conditions can be determined and the areas in which the solutions are ineffectual are also indicated.

Part 2 to this phase programs the off-line computer to solve the system fire control equations and inputs the same data to the system and off-line computers. Comparisons of the solutions provided by the computer generates data which identifies the errors associated with the mechanization of the equations by the system. The machine error is additive to the inherent error in the equations.

g. Gun Dispersion. This procedure determines the variation in the impact point of the rounds, resulting from variations in ammunition (such as charge, grain density, temperature, projectile size, weight, etc) and the reaction of the gun and turret to firing (backlash, barrel whip, barrel jump, barrel expansion, etc). This test requires the use of a large vertical target in the vicinity of the maximum range of the weapon. A boresight is used to position the weapon to the point of aim on the target. A sufficient number of bursts is fired to determine the characteristic dispersion pattern of the weapon. It is desirable that more than one weapon be used.

31

The contribution of the ammunition dispersion is separately evaluated in paragraph 2.

h. Servo Response. Servo response tests are conducted to provide information on the error sensitivity, stability, and controlability of the servo system. Data is developed in two ways:

(1) Step Input or Transient Response. This method applies a step forcing function at the input to the servo system and records the resulting output deflection of the weapon. The initial slope of the response contains information regarding the gain, velocity, and acceleration characteristics of the servo. The overshoot, oscillatory (hunting) action, and time to reach a steady state contain information relative to the servo stability and the response rate of the servo. The basic data is in the form amplitude and frequency versus time.

(2) Sinusoidal or Steady State Response. This method applies a sinusoidal forcing function at the input to the servo and records the resulting output deflection of the weapon. It is desirable also to compare the time (phase) displacement between the forcing signal and the weapon deflection. The data obtained is a direct display of servo gain and frequency response; the phase margin plot is an indicator of servo stability.

The information content of the data from both test methods is the same. Detailed procedures regarding the analysis is contained in Appendix H.

3.5.2 Data Required

a. Weapon azimuth and elevation as a function of sight azimuth and elevation (servo controlled systems, no compensation)

b. Analog and digital angle transmission signals as a function of sight azimuth and elevation (servo controlled systems, no compensation)

c. Line-of-sight azimuth and elevation angles through canopy as a function of sight azimuth and elevation angles (distortion due to refraction through canopy)

d. Distances from nominal center of rotation of sight to centers of rotation of weapons.

e. Calibration of applicable sensors:

(1) Airspeed sensor

(2) Barometric pressure sensor

(3) Range sensor

(4) Relative wind sensor

(5) Attitude sensor (displacement gyro)

(6) Attitude rate sensor (rate gyros)

(7) Temperature (ammunition) sensor

(8) Projectile velocity sensor

f. Target impact coordinates

3.6 DYNAMIC (AERIAL) TEST METHOD AND DATA REQUIRED

3.6.1 <u>Method</u>

The dynamic tests are designed to evaluate the system under operating stress. The primary purpose of the tests is the determination of the effects of the combination of the inherent component errors and operating stress. The data inputs to the system (ranging, angular position, vehicle velocity, etc), computer outputs, and weapon position are monitored directly and if the weapon is fired the target zone is monitored. If simulation is employed the data from the fire control system are compared with the simulated data. When the test effort employs realistic flight conditions, the flight path parameters relative to the target must be determined by using a monitoring system external to the aircraft, such as the PATS, and deriving the necessary data. The external monitoring system may include data gathered by instrumentation carried aboard the aircraft such as vehicle attitude, temperature, and pressure sources. The weapon system sensors may be used if calibrated and sufficiently accurate.

The selection of the operating flight conditions should be made to include the full range of stress conditions. The salient conditions are listed below:

a. Low target tracking rates, low computational and weapon positioning rates

b. Low target tracking rates, nominal computational and weapon positioning rates

c. Low target tracking rates, high computational and weapon positioning rates

d. Nominal target tracking, nominal computational and weapon positioning rates

e. High target tracking rates, high computational and weapon positioning rates

f. Target hit data for all test conditions

The data obtained are used to isolate malfunctioning components and to graphically portray the dynamic characteristics of the various system components and the error sources.

3.6.2 Data Required

The following data should be recorded immediately before and during firing and correlated with time:

a. Aircraft velocity vector

b. Aircraft heading and attitude, and rates

c. Sight angles (azimuth and elevation)

d. Weapon angles (azimuth and elevation)

e. Sight angular rates

f. Weapon angular rates

g. Sight picture (aim error)

h. Airspeed

i. Angle of attack

j. Aircraft accelerations (3-axes)

k. Laser ranging data

l. System status

(1) Firing circuit

(2) Weapons selected

(3) Sight selected

m. Sight/weapon flexure

n. Air temperature

o. Air (barometric) pressure

p. Ammunition (compartment) temperature or projectile velocity

q. Aircraft space position

r. Surface air temperature, 0-100 m

s. Surface air barometric pressure

t. Surface air relative humidity

u. Surface air winds: speed and direction, 0-100 m

v. Target impact coordinates

w. Target position

3.7 DATA REDUCTION AND PRESENTATION

A first step in evaluating data obtained from testing a fire control system is to censor the data, i.e. throw out obviously bad data in which the system was malfunctioning. Data censoring for an accuracy evaluation should include:

a. Evaluation of the sight line to target relationship

b. Examination of input-output data for malfunctioning or failed components

c. Evaluation of the effects and determination of the source of transients in the data

The censoring of data should be accomplished on the raw, unsmoothed data and the basis for discarding or disqualifying data should not include subtleties. Only obviously defective data should be discarded. Examples of data permissible to discard include:

a. Data in which the sight-line-target angular error consistently exceed the standard deviation established for target tracking proficiency (target not acquired)

b. Data in which the input-output relationship is discontinuous or inexplicably erratic

In most instances it will be obvious that data censoring almost never results in the complete loss of a set of data. Data censored from the accuracy evaluation because of a component malfunction or failure may be useful in the reliability evaluation or other phases. The criteria for censoring data for a specific type of presentation should be established prior to the start of the data collection process to avoid or minimize post facto censoring and to enhance the usefullness of all data collected. A treatment of the subject of outliers is contained in AMCP 706-113, page 17-1[5].

The forms in which data may be presented are too numerous for a detailed discussion of each form. Some of the most descriptive forms are discussed in the following paragraphs.

The fire control system consists of the target position location subsystem, the computing subsystem, the weapon position subsystem, and the ammunition and weapon subsystem.

For most evaluation purposes, each of the subsystems is considered as a separate entity and the data presentations are contrived to describe the unique performance characteristics of each. Data for analytic purposes will usually be displayed in more than one form, each form having been selected to portray specific characteristics of the data or equipment as follows:

a. Target Position Data. This data group includes the vertical and horizontal components of the target position relative to the weapon platform and the platform to target range. In general reference, it is called the sight-line data.

When the objective of the data presentation is data censoring or equipment performance validation, the sight-line data (sight vertical and horizontal angles and range to the target) is best displayed as graphic portrayals of the functions spanning the total engagement time. The graphic portrayals give the data reviewer a composite visual history of the performance of the target location system throughout the engagement. It is also useful at this point to compare abrupt changes in the sight-line angular data with the sight-line control and flight attitude data.

When performance analysis is the objective and the quantity of test data is large, it becomes useful to combine the data from all flights. At this point the plots of raw data versus time become difficult to correlate and analyze. A convenient form of data presentation is the plotting of the means of errors versus range to, and rates of change relative to, the target. This form of presentation permits

[5]AMCP 706-113, Engineering Design Handbook, Experimental Statistics, Section 4, Special Topics

the combining of data from all flights without regard to the flight duration or the target to flight path geometry. Individual error components may be plotted as functions of their corresponding rates, e.g. sight-line horizontal error versus the horizontal angular rate of the aircraft relative to the target, and range error versus the range rate of change. Additionally, system performance characteristics may be developed or substantiated by graphing sight-line error components as functions of absolute quantities, e.g. horizontal sight-line error versus target range.

Data displays of the type discussed above graphically portray the characteristics of the target position fixing system. Some of the most descriptive forms of data presentation are listed in Table 3-1.

TABLE 3-1. Data Plots

Ordinate	Abscissa	Purpose of Display
	Primary Data Plots	
Sight-line vertical error	Vertical angular velocity	Dynamic operating characteristics of vertical error sensing and control system
Sight-line horizontal error	Horizontal angular velocity	Dynamic operating characteristics of horizontal error sensing and control system
Range error	Range to target	Ranging system accuracy
Range error	Radial velocity	Ranging system sensitivity to rate of change of range
Vector sight-line error (V_e+H_e+R_e)	Aircraft slant plane angular velocity	Composite sight-line dynamic operating characteristics to aircraft flight path spectrum
Miss distance	Weapon offset angle	System performance (miss distance corrected for aim error)

TABLE 3-1. Data Plots (Concluded)

Ordinate	Abscissa	Purpose of Display
Miss distance	Radial velocity	System performance (miss distance corrected for aim error)
Miss distance	Range	System performance (miss distance corrected for aim error)
Miss distance	Angular velocity	System performance (miss distance corrected for aim error)
Weapon offset error (computed)	Range, radial and angular velocity	System performance (miss distance corrected for aim error)
	Supplementary Data Plots	
Sight-line:		
Vertical error	Range to target	Supplementary to and explanatory for characteristics observed in primary plots
Horizontal error	Range to target	Supplementary to and explanatory for characteristics observed in primary plots
Vertical error	Aircraft velocity	Supplementary to and explanatory for characteristics observed in primary plots
Horizontal error	Aircraft velocity	Supplementary to and explanatory for characteristics observed in primary plots

b. Computer Data. This data group is composed of the target position, meteorological, aircraft motion and attitude, ammunition ballistics data at the input, the fire control equations for ballistics and motion compensation, and the computed weapon offset angles. The target position data has been treated as a separate subject. The accuracy of meteorological data sensors, (crosswind velocity and direction, air temperature, air density, etc) is determined by laboratory experiment. While it is necessary to record these data, it is not conveniently possible to check its accuracy when the aircraft is in flight. The primary uses for these data are the determination that the sensors were functioning and to provide input data for the off-line computer. Comparisons of these data with externally collected meteorological data serves only to verify the functioning of sensors but does not, in the absence of elaborate on-board instrumentation, yield accuracy.

The standard ammunition ballistics data are predetermined information which is stored in the computer. Although it may be modified within the computer because of the measured meteorological conditions, the cost versus yield factor usually precludes the extraction of the actual data from the computer. The effects of modification of the standard ballistics by the fire control computer are best determined during the static accuracy evaluation of the computer.

The aircraft attitude data are essentially part of the target position data, since they are used to correct the sight-line data to the computing reference system, when the flight attitude is other than the boresight attitude. These data are included in the computer data group solely because the more advanced systems correct the sight-line through matrix rotation. The more rudimentary systems use a more direct approach such as sensing the attitude and sight-line angles with synchros and using resolvers to perform the necessary angle corrections.

Aircraft linear motion data are also part of the sight-line data since they relate the aircraft positional change to the target. These data are also used in the computations of weapon offset angle to compensate for velocity components added to the projectile by motion of the platform. Since these data are representative of the velocity of the aircraft along the flight path, its accuracy can be determined from data obtained by monitoring the position of the aircraft relative to time. The most descriptive presentation is a graphic display of velocity errors plotted against the actual velocity. The errors are derived by comparing the velocities recorded on board the aircraft with data derived from ground based observation points.

The fire control equations must be treated in at least two ways: to show the relative accuracy of the equations when compared to ideal or theoretically correct equations and to show the accuracy and adequacy of the delivered hardward. The first is accomplished by comparing the predictions derived by solving, off-line, the same problems with the theoretically correct equations and the equations mechanized by the fire control. The inputs to the theoretically correct equations must include all the correction terms for ballistics and motion to demonstrate the effects of truncation in the data or of the equations as used by the fire control system. To accomplish the second, the solutions provided by the fire control computer under inflight conditions are compared with solutions to the same problems by an off-line computer using the recorded inflight data as inputs and solving the system fire control program.

The purpose of the first comparison is to demonstrate the inherent accuracy of the fire control system under idealized simulated conditions. This accuracy can be expected to degrade in a realistic environment. Contributors to the degradation are unstable flight, servo lag, sensor error, data sampling rate, computer cycle time, and data conversion losses. This degradation is demonstrated in the second comparison.

A third method is to derive the necessary inputs to the fire control equations through external instrumentation under flight conditions and solve the equations. Comparison of these solutions with those provided by the system yields the overall accuracy of the fire control system (including sensors and computer).

Analysis of the computer data is neither simple nor direct except as it concerns the magnitude of the error. Even this can be misleading because it can be shown that errors in the target position data result in additional errors in the computed weapon offset angles. The more useful data presentations are derived by plotting the errors as functions of angular velocity, range and range rate of change, and theoretically correct weapon offset angles. The most revealing presentation is developed by plotting the errors and the error rates as functions of the magnitude of the required correct weapon offset angles. The latter presentations graphically illustrate the performance of the fire control over its full operating range.

A sample program is included in Appendix E for computation of weapon lead and superelevation angles. The program inputs are:

(1) Aircraft velocity vector

(2) Wind velocity vector

(3) Aircraft heading, pitch, and roll angles

(4) Sight elevation and azimuth (train) angles

(5) Slant range

(6) Air density

(7) Muzzle velocity

(8) Ballistic equation coefficients for the particular projectile

The program is written in BASIC to be run on a desk top programmable calculator. The computed lead angle does not take into account target motion. Target motion, if any, should be compensated for by predicting the line of sight required to hit the future position of the target. The predicted line of sight based on aircraft and sight angular rates or actual target motion may be used in the given program.

c. Weapon Position Data. This data set has two components, the vertical and horizontal positions of the weapon. Errors in these coordinates are derived by comparing the difference between the sight-line and weapon position angles with the computed weapon offset angles. This procedure yields the error in the developed weapon offset angle which can be plotted to graphically illustrate the combined conversion and servo losses between the computer output and the weapon. For analytic purposes these errors can be plotted as functions of angular velocity, range, range rate, required offset angle, and rate of change of offset angle. A sometimes useful plot is the error rate versus the magnitude of the required offset angle.

d. Ammunition and Weapon Data. The ammunition and weapon data are not addressed as topics for presentation and analysis because of the difficulties encountered in obtaining the types of information required (propellant temperature, muzzle velocity, barrel expansion, firing order of rounds in the impact zone, etc) under flight conditions. Additionally, the method by which the remaining data components (platform linear velocities, weapon angular velocities, platform accellerations, etc) combine to develop the dynamic dispersion at the impact zone is not well defined.

e. System Performance. The ultimate data presentation is considered to be the presentation relating the sight-line and rounds impact point to the aiming reference. This portrayal is one which is sometimes

misinterpreted because it is characteristically assumed that by transposing the aiming reference into coincidence with the sight-line, any remaining bias in the shot distribution pattern is due entirely to the weapon and ammunition. This assumption is not strictly true. It can be demonstrated that even relatively small (± 5 mil) errors in the sight-line not only propagate in total through the system (weapon position = sight-line angle + computed offset angle) but produce computational errors as well. (Offset angle = f (observed angle) +f (observed range) +f (gravity) +f (platform velocity) +f (projectile velocity)) The transposition logic also includes the erroneous assumption that there is no error contribution due to the range value input to the system. When the range to the target is short relative to the effective range of the weapon, the effects of the computed error caused by the error in the sight-line will be negligible. The computed error increases primarily with increased range to the target and platform velocity.

The most useful function which the plots of rounds impact versus point of aim serve is to verify the predictions of accuracy which are made from the treatment accorded the large quantity of data obtained when the system is performing its normal tracking and computing functions prior to and after the firing of the weapon. These data encompass the entire spectrum of target engagement conditions and its use should sucessfully predict the behavior of the system during the short interval of the firing engagement within the limits of a small error budget. The analysis based upon treatment of the fire control performance data during the target tracking phases should substantiate and be substantiated by the system performance during the firing interval and serves as the data base for evaluating the system capability under a wide variety of operating conditions.

Examples of some of the suggested data presentations are presented in the following paragraphs.

f. Analysis of Typical Target Engagement Data. The plots in Figure 3-2 contain 7.5 seconds of sight-line data during a target tracking and firing engagement. The weapon was fired at approximately 2 seconds after the plots began (not the start of the engagement). The upper traces depict the angular displacement between the sight reticle and the target while the second traces graph the difference (error) in the angular velocities of the sight and the target. The fire control from which these data were recorded computes the weapon offset angle by the relating target future position with sight-line angular rate and target range (target range is converted to projectile time of flight to derive $\Delta\theta = f(\omega, T_f)$). The errors in the sight-line (x mils azimuth and y mils elevation) point the weapon away from the target by identical amounts. The rate error causes the computer to produce an incorrect

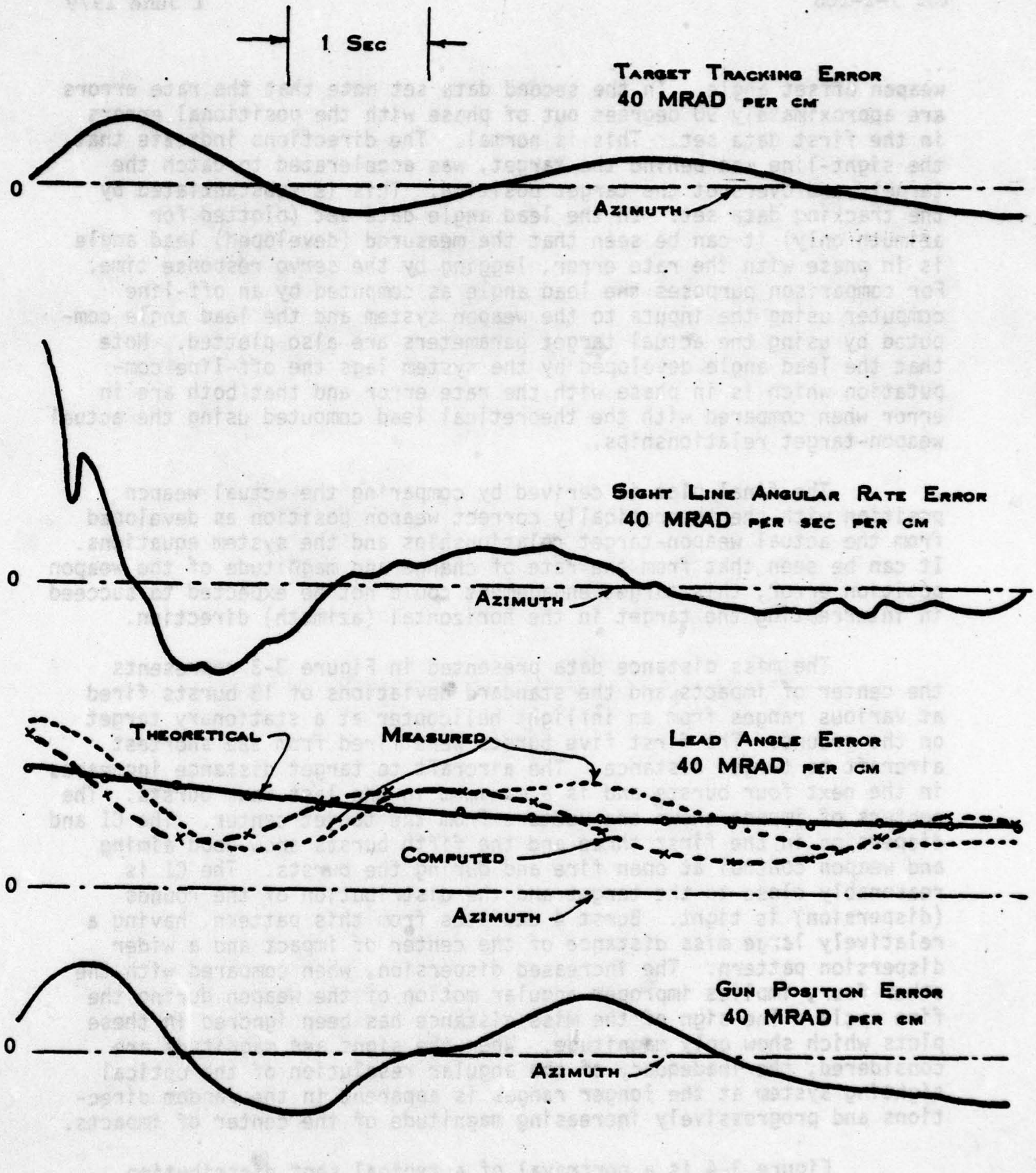


FIGURE 3-2. TYPICAL TARGET ENGAGEMENT DATA

weapon offset angle. In the second data set note that the rate errors are approximately 90 degrees out of phase with the positional errors in the first data set. This is normal. The directions indicate that the sight-line was behind the target, was accelerated to catch the target, and overshot the target position. This is substantiated by the tracking data set. In the lead angle data set (plotted for azimuth only) it can be seen that the measured (developed) lead angle is in phase with the rate error, lagging by the servo response time. For comparison purposes the lead angle as computed by an off-line computer using the inputs to the weapon system and the lead angle computed by using the actual target parameters are also plotted. Note that the lead angle developed by the system lags the off-line computation which is in phase with the rate error and that both are in error when compared with the theoretical lead computed using the actual weapon-target relationships.

The final plot is derived by comparing the actual weapon position with the theoretically correct weapon position as developed from the actual weapon-target relationships and the system equations. It can be seen that from the rate of change and magnitude of the weapon position error, this target engagement could not be expected to succeed in intercepting the target in the horizontal (azimuth) direction.

The miss distance data presented in Figure 3-3 represents the center of impacts and the standard deviations of 13 bursts fired at various ranges from an inflight helicopter at a stationary target on the ground. The first five bursts were fired from the shortest aircraft to target distance. The aircraft to target distance increases in the next four bursts and is a maximum in the last four bursts. The centers of impact shown are vectors from the target center. The CI and dispersion in the first three and the fifth bursts show good aiming and weapon control at open fire and during the bursts. The CI is reasonably close to the target and the distribution of the rounds (dispersion) is tight. Burst 4 deviates from this pattern, having a relatively large miss distance of the center of impact and a wider dispersion pattern. The increased dispersion, when compared with the other four, implies improper angular motion of the weapon during the fire cycle. The sign of the miss distance has been ignored in these plots which show only magnitude. When the signs and magnitude are considered, the inadequacy of the angular resolution of the optical sighting system at the longer ranges is apparent in the random directions and progressively increasing magnitude of the center of impacts.

Figure 3-4 is a portrayal of a typical shot distribution pattern in a burst. Also included on the plot is the definition of various terms used in describing the burst pattern.

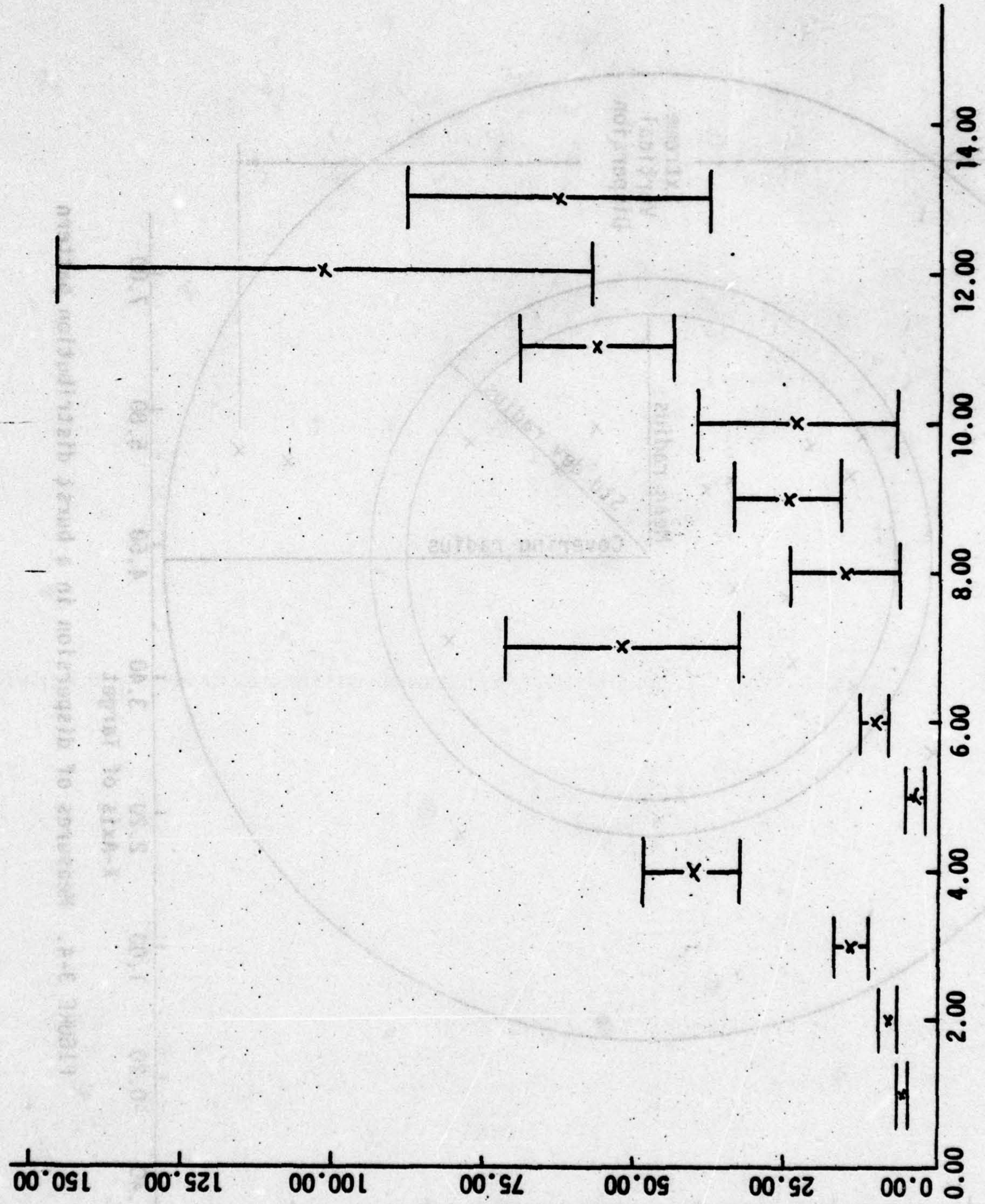


FIGURE 3-3. Mean and standard deviation of the distance between center of impact and Target plotted against burst number.

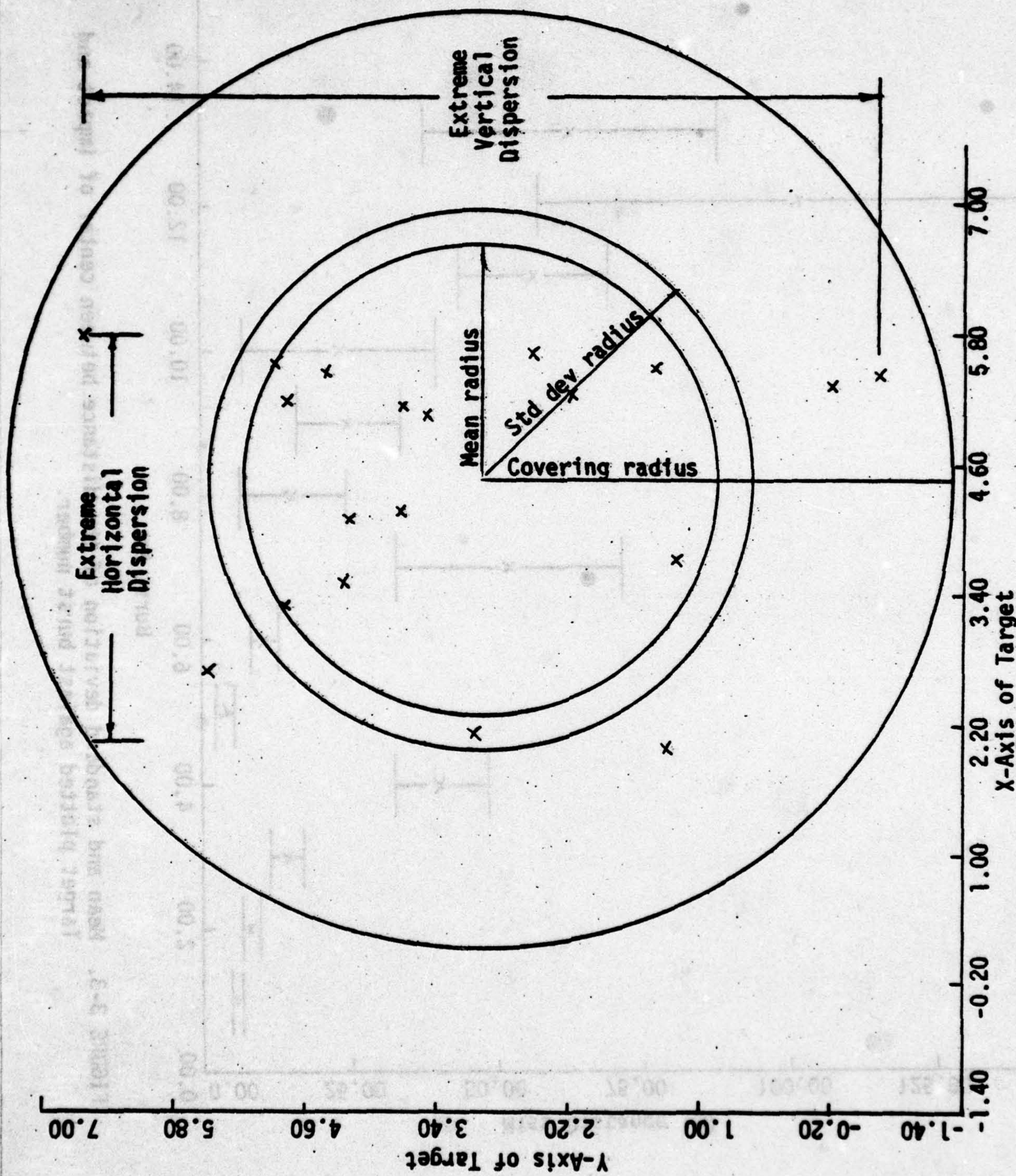


FIGURE 3-4. Measures of dispersion in a burst distribution pattern

Figure 3-5 graphically relates the target reference, point of aim, burst bias and circular probable error for six bursts, each of 3 seconds duration fired from a helicopter in flight. The centers of impact are characteristically above and to the left of the point of aim which in these instances are the points of aim at open fire. The dispersions about the center of impacts can be related to the ranges at which the bursts were fired and to improper motion of the sight and weapon during the firing interval. When the mean point of aim is used the magnitude of the displacement between the bias (center of impact) and the point of aim is reduced and becomes more consistent. The directions remain unchanged.

Recommended changes to this publication should be forwarded to Commander, U. S. Army Test and Evaluation Command, ATTN: DRSTE-AD-M, Aberdeen Proving Ground, MD 21005. Technical information may be obtained from the preparing activity: Commander, U. S. Army Yuma Proving Ground, ATTN: STEYP-MAA, Yuma, AZ 85364. Additional copies are available from the Defense Documentation Center, Cameron Station, Alexandria, VA 22314. This document is identified by the accession number (AD No.) printed on the first page.

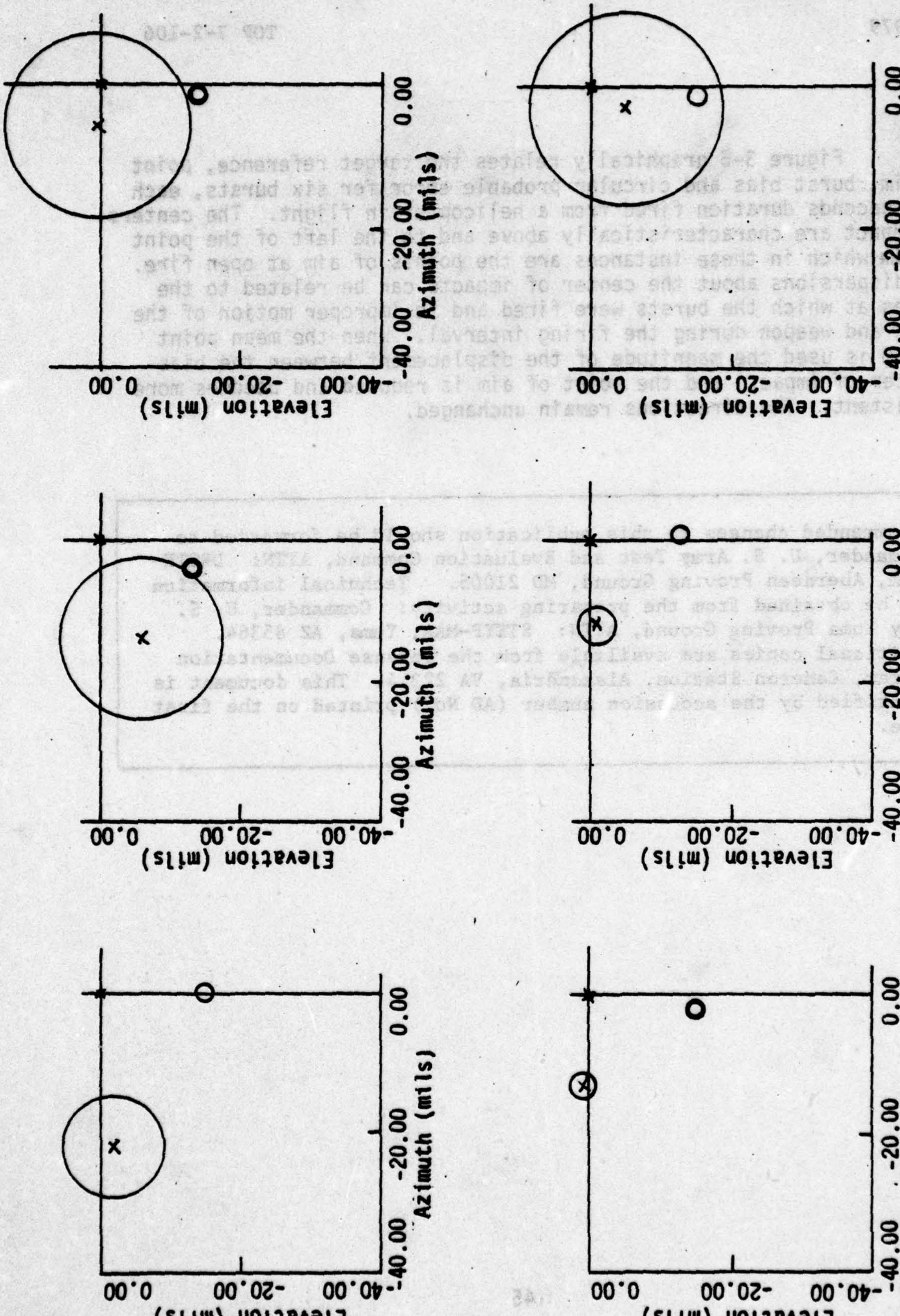


FIGURE 3-5. Two-dimensional relationship between burst pattern and sight line with respect to target center. The line of sight is indicated by the small circle, the burst pattern is centered at the cross.

APPENDIX A. FACILITIES

Targets

Based upon range (distance) requirements, weapon system characteristics, and conditions of use the appropriate types, sizes, and locations of targets will be selected. Target types may include hard and soft vertical targets, horizontal targets, moving targets, and realistic targets.

Hard vertical targets are constructed of plywood on a supporting wooden framework or of other material such as armor plate if terminal effects are to be observed. A crane may be required for target patching. A soft target of cloth stretched across a frame is generally used with explosive projectiles to avoid functioning and target destruction. The target frame may be constructed to pivot about the lower edge so that it can be laid horizontal for scoring and repair. The practical limit of vertical target size is between 20 and 40 meters square.

Horizontal targets are used when dispersion is too great for a vertical target, the line of fire is more nearly normal to a horizontal plane, and when dispersion in a horizontal plane is required for analysis. The earth becomes the horizontal target plane and contrasting markers are positioned in the target area to serve as reference. Scoring is accomplished by filming impacts from an overhead helicopter modified to provide a camera port in the bottom. Target size is limited only by impact signature resolution. A problem encountered with horizontal targets is obscuration of subsequent impacts by smoke or dust (or foam if in water) from the first few rounds. The graze impact media (sand, macadam, sod, mud or earth) are special horizontal targets for fuze tests.

Nonmaterial targets employing acoustic, light, radar and possibly other forms of projectile sensing have been developed and used with varying degrees of success. Most of these systems suffer from lack of physical evidence of impact location, some do not provide more than a gross indication of the path of the projectile through the target plane. However, if a reliable and accurate automatic scoring system does become available it will greatly improve the efficiency of many accuracy tests.

A tank-size moving target may be used with point target weapon systems such as antitank guided missiles. The target is mounted above a vehicle chassis which is protected by an embankment. The remotely

controlled vehicle is guided by fixed tracks or other means. This arrangement provides a test of the weapon system ability to compute lead angle under the optimal conditions of target visibility and familiarity.

Realistic targets are not as often used because of difficulty in isolating, measuring and analyzing the many sources of error such as detection and recognition. The problem may be compounded by complex target shapes and lack of data on misses. Nevertheless, realistic targets do provide essential qualitative verification of overall system performance.

Realistic targets may take the form of real or mockups of automotive vehicles and tanks, silhouettes of personnel, bunkers and other battlefield targets in various degrees of cover and concealment.

Target locations are governed by area requirements and availability. In general, existing targets on established ranges should be used if possible to avoid the expense of new target construction.

Test Stands

An aircraft armament subsystem may require environmental or other tests in which an entire aircraft cannot be used. Depending upon the test requirement, a special mount or test stand may be built which simulates the aircraft structure to a degree.

The simplest test stand is that required for a pintle-mounted machine gun normally exposed to the elements when installed on an aircraft. The design requirements for this type of test stand are:

(1) Accurate location of mounting points

(2) Adequate strength and rigidity

(3) Materials similar to those used in the mounting hardware of the aircraft, not dissimilar metals subject to corrosion

(4) Adjustable safety stops to prevent flexible guns from being slewed beyond safety limits for the test phase

(5) Human engineering to provide for operation and maintenance accessibility at least equal to that provided on the aircraft

Test stands for armament subsystems more complex than a pintle-mounted machine gun must be carefully designed to meet additional

requirements. In some cases a mockup or nonflyable aircraft will provide the only acceptable solution. Some of the additional requirements are:

(6) Appropriate relative location of components

(7) Appropriate environmental protection of components

(8) Electrical power of correct voltages (AC or DC) and current

(9) Electrical grounds

(10) Electrical switching (relays, circuit breakers) normally provided by the aircraft

(11) Hydraulic pressure and flow if required, equivalent to that provided by the aircraft

(12) Mobility (wheels, jacks)

(13) Tie downs

(14) Remote operation

(15) Shock and vibration fixture use

Test stand preparation must begin well in advance of testing in order to allow time for procurement of long lead time items such as special power supplies, electrical connectors, hydraulic fittings, and light metal alloys. Close coordination with the test sponsor is required to insure proper design of the test stand.

51

APPENDIX B. COMPUTATION OF HIT PROBABILITY

A popular measure of weapon system accuracy is hit probability (the probability of hitting a given target with specific projectiles under certain conditions). There are several different types of hit probability, e.g. single-shot hit probability, first round hit probability, engagement hit probability, etc.

Consider a rectangular target with dimensions A by B and assume that the horizontal and vertical impacts of the shot pattern are independent, normally distributed random variables. This bivariate normal distribution is assumed to be centered at the center of impact of the shot pattern, although it might also be assumed to be centered at the center of aim. Biases in the impact data which do not contribute to P_{ssh}, e.g. the point of aim and the point of reference, should be removed, if possible.

The equations for determining single-shot hit probability employ the sample mean and the sample standard deviation as estimates of the shot-group pattern. The equations are:

$$P_x = \int_{\frac{-A/2-\bar{X}}{S_x}}^{\frac{A/2-\bar{X}}{S_x}} \frac{1}{\sqrt{2\pi}} \exp\left[-1/2\ t^2\right] dt$$

$$P_y = \int_{\frac{-B/2-\bar{Y}}{S_y}}^{\frac{B/2-\bar{Y}}{S_y}} \frac{1}{\sqrt{2\pi}} \exp\left[-1/2\ t^2\right] dt$$

and

$$P_{ssh} = P_x P_y$$

where

$\bar{X}$, $\bar{Y}$ = sample mean in the x and y direction, respectively

S_x, S_y = sample standard deviation in the x and y direction, respectively

A, B = target dimensions in the x and y direction, respectively

The integration of the normal probability density functions cannot be carried out in closed form. Solutions can be readily evaluated, however, by the following BASIC calculator program:

```
 10  DISP "MEAN";
 20  INPUT M
 30  DISP "STD DEV";
 40  INPUT S
 50  PRINT "MEAN="M;"STANDARD DEVIATION="S
 60  PRINT
 70  DISP "X";
 80  INPUT X
 90  STANDARD
100  PRINT "X="X;
110  FIXED 8
120  PRINT " PROBABILITY="0.5+SGN(X-M)*FNA(X)/2
130  STANDARD
140  GOTO 70
150  END

 19  DEF FNA(X)
 29  Z=ABS(X-M)/S
 39  A=0
 49  IF Z>0 THEN 69
 59  GOTO 169
 69  T=0.7071067812*Z
 79  S1=T
 89  Y2=(Z*Z)/2
 99  D1=1
109  REMARK:ACCUMULATE SUM OF TERMS
119  D1=D1+2
129  T=T*(Y2*2/D1)
139  S1=S1+T
149  IF (T/S1)>1E-10 THEN 119
159  A=1.128379167*S1*EXP(-Y2)
169  RETURN A
179  END
```

As an example of hit probability calculation, consider the following hypothetical situation, obtained from firing at a 9-meter square target at a 1000-meter range:

$\bar{X}$ = 4.0 mils S_x = 2.0 mils

$\bar{Y}$ = 2.0 mils S_y = 1.0 mil

Also $X_1 = \frac{-4.5}{1000} = -4.5$ mils, $X_2 = \frac{4.5}{1000} = 4.5$ mils

X_1 is the coordinate of the left edge of the target and X_2 is the coordinate of the right edge.

The values for $\bar{X}$, S_x, X_1, and X_2 are entered into the calculator:

MEAN= 4   STANDARD DEVIATION= 2

X_1 = X=-4.5   PROBABILITY= 0.00001069
X_2 = X= 4.5   PROBABILITY= 0.59870633

The difference in probabilities is the area under the normal curve from X_1 to X_2

$$P_x = 0.59870633 - 0.00001069 = 0.59869564$$

Similarly, enter $\bar{Y}$, S_y, Y_1, and Y_2:

MEAN= 2   STANDARD DEVIATION= 1

Y_1 = X=-4.5   PROBABILITY= 0.00000000
Y_2 = X= 4.5   PROBABILITY= 0.99379033

The area under the normal curve between Y_1 and Y_2 is 0.99379033. This is P_y.

This product of these two probabilities (rounded off), $P_H = P_xP_y = 0.5940$, is the hit probability at a range of 1000 meters.

In general, hit probability will vary as a function of range and target size, becoming smaller as the range increases and the size of the target decreases. A useful curve for analysis is the single-shot hit probability P_{ssh} versus range. To provide the necessary data, impact coordinates are recorded at all firing ranges of interest for which the curve is to be plotted.

When the target and helicopter are both moving, the hit probability relationship becomes more complicated and a more exact description of a system might involve families of curves depending on such parameters as speed, altitude, test course, etc (Ref 3).

The engagement hit probability P_{en} is the probability of obtaining a hit with at least one shot during an engagement. The single-shot probability of not hitting a target, under specific conditions, is:

$$Q_{ssh} = 1 - (P)_{ssh}$$

and the probability of not hitting during the engagement, where independence of shots can be assumed, is:

$$Q_{eh} = (Q_{ssh_1})\ (Q_{ssh_2})\ (Q_{ssh_3})\ \ldots\ldots\ (Q_{ssh_n})$$

where subscripts 1 through n represent individual shots fired in the engagement, each of which may have a different probability of not hitting.

Other approaches to computation of hit probability include the binomial method where the numbers of hits on a target are counted as successes and the numbers of misses are counted as failures. The binomial series is used for computation of reliability of hitting (hit probability) at various confidence levels.

An OC curve presenting confidence as a function of true hit probability can be prepared.

The non-central chi-square distribution can be used for computation of hit probability where bias exists. That method is beyond the scope of this TOP.

APPENDIX C. STATISTICAL CONCEPTS

STATISTICAL CONCEPTS FOR COMPARATIVE TESTING AND EVALUATION

Confidence Intervals

When estimating the value of some parameter, such as the mean or standard deviation of a population, it is useful to employ the concept of confidence intervals. This asserts the probability that the interval estimate of the parameter is doing its job of containing the parameter it is supposed to estimate.

Consider the case of the sample mean $\overline{X}$ for random samples of size n from a normal population with mean μ and variance σ^2. If $\phi_{\alpha/2}$ is the integral of the standard normal density from $z_{\alpha/2}$ to ∞, we can say that there is probability $(1-\alpha)$ that the random variable $\frac{\overline{X}-\mu}{\sigma/\sqrt{n}}$ will take on a value between $-z_{\alpha/2}$ and $z_{\alpha/2}$. Analytically

$$-z_{\alpha/2} < \frac{\overline{X}-\mu}{\sigma/\sqrt{n}} < z_{\alpha/2}$$

or

$$\overline{X}-z_{\alpha/2}\cdot\frac{\sigma}{\sqrt{n}} < \mu < \overline{X}+z_{\alpha/2}\cdot\frac{\sigma}{\sqrt{n}}$$

Thus, we have a degree of confidence equal to $1-\alpha$ that the true mean will fall within the above range of values based on the sample mean $\overline{X}$ obtained in a sample. Values of $z_{\alpha/2}$ may be determined from tables of the normal distribution. Note that other intervals would also have been employed, such as $\pm z^2{}_{\alpha/3}$.

When σ is not known, the sample standard deviation s could be used. In this case the statistic $\frac{\overline{X}-\mu}{s/\sqrt{n}}$ has a t distribution with n-1 degrees of freedom and the confidence interval becomes

$$\overline{X}-t_{\alpha/2,\ n-1}\cdot\frac{S}{\sqrt{n}} < \mu < \overline{X}+t_{\alpha/2,\ n-1}\cdot\frac{S}{\sqrt{n}}$$

As an example, consider the observations shown in Table C-1 of sight line error grouped according to angular velocity.

TABLE C-1. Observations of Sight Line Error

Observation	No. of Observations				
	90	65	45	35	15
Angular velocity, radians per second	0 to 0.15	0.151 to 0.2	0.21 to 0.5	0.51 to 0.75	0.751 to 1.00

A confidence interval for each group can be determined using the t distribution. At a 95 percent level, this states that we can be 95 percent confident that the true mean of the population lies within the calculated interval. When the number of observations exceeds 30, the normal distribution may be used without introducing significant error. This is the case for the first four groups (90, 65, 45, 35). The fifth group, however, must utilize the t distribution. A typical result is depicted in Figure C-1. The means and 95 percent confidence intervals for each of the five groups are plotted.

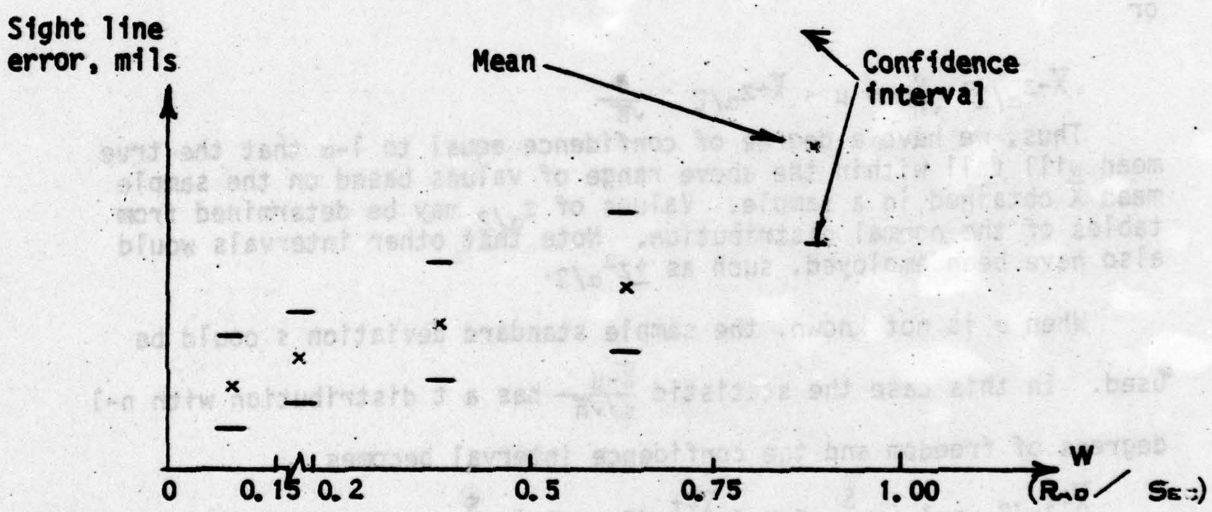


FIGURE C-1. Sight Line Error versus Angular Velocity

As the number of observations decreases, the interval of 95 percent confidence becomes larger. In order to maintain a fixed error interval throughout the range of values, the level of confidence must be adjusted

accordingly. For example, in Figure C-1, the confidence level for the fifth group must be decreased to obtain the same sight line error interval as that of the first group.

Confidence intervals can also be specified for the sample variance. Here the statistic $\frac{(n-1)s^2}{\sigma^2}$ has a χ^2 distribution with n-1 degree of freedom and for a degree of confidence $(1-\alpha)$

$$\frac{(n-1)s^2}{\chi^2_{\alpha/2,n-1}} < \sigma^2 < \frac{(n-1)s^2}{\chi^2_{1-\alpha/2,n-1}}$$

Values of the t and χ^2 distributions are tabulated in standard statistics textbooks or may be computed from available BASIC calculator programs.

Regression Analysis

System performance data may be analyzed to determine whether or not a functional relationship exists between weapon system performance, e.g. weapon system accuracy, and some independent variable, e.g. airspeed, altitude, etc. A statistical analysis may be made to determine, for example, if performance decreases systematically as the variable is increased progressively to higher levels. If the data exhibits this characteristic, certain internal elements of the system that were designed to correct for the variable in question may not be functioning correctly and would be a probable cause of failure.

Regression analysis may be used to determine if one quantity can be predicted in terms of the other. Linear regression concerns examination of data on the dependent variable which corresponds to preset values of the independent variable. The relationship can be written as

$$y = a + b x$$

where

x = independent variable
y = dependent
a, b = constants

An assumption of normality for the distributions of random variables x and y and a common standard deviation are reasonable for this problem. More details on regression analysis may be found in References 2 and 8.

Analysis of Variance

In performing statistical tests, it may be necessary to determine if one type of test item is better than another. The procedure in this case is to design the experiment not only to compare the merits of the test item under general conditions, but also to test whether other variables affect the performance. The arrangement of the equipment for such a test consisting of N runs is illustrated in Table C-2.

TABLE C-2. Comparative Evaluation

Test Run	Test Equipment	Condition 1	Condition 2	Condition 3
1	A	L	G	C
2	B	H	P	C
⋮	⋮	⋮	⋮	⋮
N	A	H	D	F

This means that the first test run is performed with test equipment A under conditions L, G, and C. It is customary to arrange this type of scheme so that each test item is used once under each possible combination of conditions. This is referred to as a completely balanced design.

An important consideration is randomization, i.e. randomly selecting the order in which the test runs are to be performed. This combats against extraneous factors affecting the results, e.g. deterioration of the equipment.

Another factor of importance is replication obtained by repeating all or part of the experimental scheme. This yields an estimate of chance variation, and is used to decide whether observed differences between sample means are significant or can they be attributed to chance.

APPENDIX D. FIRE CONTROL PROGRAM

```
10  DIM A[3],B[3],C[8],D[3],E[3],F[3],G[3],H[3,3],P[3,3],R[3,3],
      S[3,3],V[3],W[3]
20  X=0
30  DEG
40  DIM X[3]
50  PRINT TAB30"FIRE CONTROL"
60  PRINT
70  PRINT TAB50"THORMON ELLISON"
80  PRINT TAB50"23 APRIL 1976"
90  PRINT
100 PRINT "THIS PROGRAM USES BRL BALLISTIC EQUATIONS FOR AIRCRAFT"
110 PRINT "WEAPONS TO COMPUTE REQUIRED LEAD AND SUPERELEVATION ANGLES."
120 PRINT "INPUTS ARE:"
130 PRINT TAB10"AIRCRAFT VELOCITY, INERTIAL COORDINATES"
140 PRINT TAB10"WIND VELOCITY, INERTIAL COORDINATES"
150 PRINT TAB10"GRAVITY VECTOR, INERTIAL COORDINATES"
160 PRINT TAB10"AIRCRAFT HEADING, PITCH, AND ROLL ANGLES"
170 PRINT TAB10"SIGHT AZIMUTH AND ELEVATION ANGLES"
180 PRINT TAB10"SLANT RANGE"
190 PRINT TAB10"MUZZLE VALOCITY"
200 PRINT TAB10"STANDARD AND ACTUAL ATMOSPHERIC DENSITY"
210 PRINT
220 PRINT "ALL INPUT DATA UNITS SHOULD BE METERS, SECONDS AND DEGREES."
230 PRINT
240 PRINT "THE FOLLOWING SPECIAL FUNCTION KEYS ARE USED:"
250 PRINT TAB10"KEY F0, INTRODUCTION"
260 PRINT TAB10"KEY F1, DATA INPUT"
270 PRINT TAB10"KEY F2, COMPUTATION OF LEAD AND SUPERELEVATION ANGLES"
280 PRINT TAB10"KEY F3, DATA PRINT"
290 PRINT TAB10"KEY F18, FNA(X)"
300 PRINT TAB10"KEY F19, FNB(X)"
310 PRINT
320 END
```

```
  1 REM DATA INPUT
 11 DISP "A/C VEL., N,E,UP";
 21 INPUT D[1],D[2],D[3]
 31 DISP "WIND VEL., N,E,UP";
 41 INPUT E[1],E[2],E[3]
 51 DISP "A/C HEADING, PITCH, ROLL ANGLES";
 61 INPUT H,P,R
 71 DISP "SIGHT AZIMUTH, ELEV ANGLES";
 81 INPUT TO,EO
 91 DISP "SLANT RANGE";
101 INPUT XO
111 DISP "MUZZLE VELOCITY";
121 INPUT BO
131 DISP "AIR DENSITY, STANDARD, ACTUAL";
141 INPUT PO,PT
151 PRINT
161 END


  2 REM COMPUTATION
 12 E1=FNC(X)
 22 PRINT "LEAD="T1;"SUPERELEVATION="E1"DEGREES"
 32 PRINT
 42 END

  3 PRINT TAB20"INPUT DATA"
 13 X=FNP(X)
 23 END

 16 DEF FNC(X)
 26 REM COMPUTATION
 36 MAT B=ZER
 46 B[1]=1
 56 X=FNA(X)
 66 B2=FNB(X)
 76 B1=SQR(1-B2*B2-B3*B3)
 86 X=ABS((B1-B[1])/B1)+ABS((B2-B[2]/B2)+ABS((B3-B[3]/B3)
 96 B[1]=B1
106 B[2]=B2
116 B[3]=B3
126 IF X>1E-05 THEN 66
136 T1=ATN(-B2/B1)
146 E1=ATN(B3/SQR(B1*B1+B2*B2))
156 RETURN E1
```

```
17  DEF FNP(X)
27  PRINT "AIRCRAFT VELOCITY; N="D[1];"E="D[2];"UP="D[3]
37  PRINT "WIND VEL; N="E[1];"E="E[2];"UP="E[3]
47  PRINT "A/C HEADING="H;"PITCH="P;"ROLL="R
57  PRINT "SIGHT AZIMUTH="TO;"SIGHT ELEVATION="EO"DEGREES"
67  PRINT "SLANT RANGE="XO"METERS"
77  PRINT "MUZZLE VELOCITY="BO"M/S"
87  PRINT "AIR DENSITY/STANDARD="P1"/"PO
97  PRINT
107 RETURN X


18  DEF FNA(X)
28  REM BALLISTIC COEFFICIENTS
38  DATA 1.043E-06,2.151E-12,-3.047E-04,6.324E-08,0.34,-1.02,
      -1.86,0.024
48  RESTORE
58  MAT READ C
68  B[1]=SQR(1-B[2]+2-B[3]+2)
78  MAT H=IDN
88  MAT P=IDN
98  MAT R=IDN
108 H[1,1]=COSH
118 H[1,2]=-SINH
128 H[2,1]=SINH
138 H[2,2]=COSH
148 P[2,2]=COSP
158 P[2,3]=SINP
168 P[3,2]=-SINP
178 P[3,3]=COSP
188 R[1,1]=COSR
198 R[1,3]=-SINR
208 R[3,1]=SINR
218 R[3,3]=COSR
228 MAT S=IDN
238 S[1,1]=COSTO*COSEO
248 S[1,2]=SINTO*COSEO
258 S[1,3]=SINEO
268 S[2,1]=-SINTO
278 S[2,2]=COSTO
288 S[3,1]=SINEO*COSTO
298 S[3,2]=-SINTO*SINEO
308 S[3,3]=COSEO
318 RETURN X
```

```
19  DEF FNB(X)
29  MAT G=ZER
39  G[3]=-32.2*12/39.37
49  MAT X=H*G
59  MAT G=P*X
69  MAT X=R*G
79  MAT G=S*X
89  MAT X=H*D
99  MAT A=P*X
109 MAT X=R*A
119 MAT A=S*X
129 T2=XO/(BO*B[1]+A[1]+(0.5*G[1]*XO/(BO*B[1]+A[1])))
139 MAT X=H*E
149 MAT W=P*X
159 MAT X=R*W
169 MAT W=S*X
179 MAT V=(BO)*B
189 MAT V=V+A
199 MAT V=V-W
209 V+SQR(V[1]↑2+V[2]↑2+V[3]↑2)
219 T1=T2*(P1/PO)*V*(C[1]*XO+C[2]*XO↑2)
229 T=T2+T1
239 G1=T/(2+(P1/PO)*V*T*(C[3]+C[4]*XO))
249 B2=-(A[2]+G[2]*G1+C[5]*T)/BO
259 B2=B2+C[6]*(T1/XO)*W[2]
269 B2=B2+C[8]*(B[3]*(A[3]-W[3])-B[3]*(A[1]-W[1]))/V
279 B3=-(A[3]+G[3]*G1)/BO
289 B3=B3+C[7]*(T1/XO)*W[3]
299 B3=B3+C[8]*(B[2]*(A[1]-W[1])-B[1]*(A[2]-W[2]))/V
309 RETURN B2
```

```
4   E3=E1
14  X4=XO
24  FOR E4=0 TO E3 STEP 0.1
34  EO=E4
44  XO=X4
54  X=FNC(X)
64  IF ABS((E1+E4-E3)/E3)<1E-05 THEN 94
74  X4=XO*(1-0.5*(E1+E4-E3)/E3)
84  GOTO 44
94  PRINT "E4="E4;"H="XO*SINE4;"E1="E1"XO="XO
104 NEXT E4
114 PRINT
124 END
```

APPENDIX E. ANGLE MEASUREMENT AND TRANSMISSION

The entire fire control problem revolves about measurement, operations on, and transmission of angles. Various types of angle measurement transducers or angle encoders include synchros, synchro resolvers, rotary potentiometers, and incremental encoders. Of these, the synchros and synchro resolvers find greatest application to aircraft armament.

Synchros (Fig. E-1) are rotary transformers in which the electromagnetic coupling between stator and armature determines the electrical output amplitude.

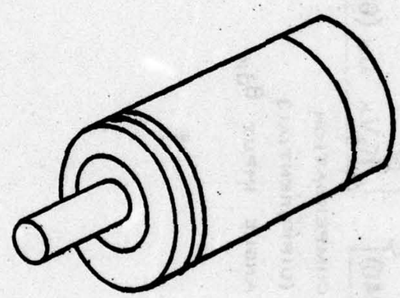


FIGURE E-1. Synchro

Synchro types commonly used in aircraft systems include the control transmitter (CX), control differential transmitter (CDX), and control transformer (CT). A schematic of a hypothetical fire control data transmission system (similar to that of the M5) is provided in Figure E-2.

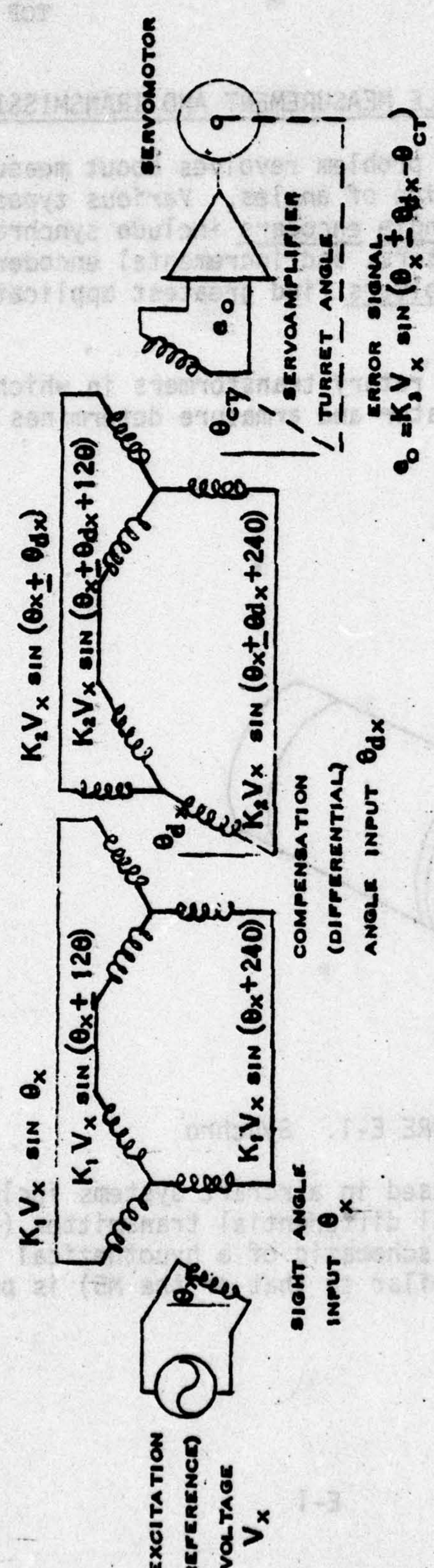


FIGURE E-2. Fire Control Data Transmission from Sight to Turret

The input to the control transmitter (CX) on the sight is the sight angle (elevation or azimuth) and an excitation voltage Vx which may be 26V, 400 Hz transformed from the aircraft inverter. The sight angle is transmitted to the control differential transmitter (CDX) where a compensation angle for superelevation, lead or other factors may be added. The combined sight and compensation angle is then transmitted to the turret mounted control transformer (CT).

The turret angle (θ_{ct}) should equal the combined sight and compensation angle ($\theta_x \pm \theta_{dx}$). If it does not, an error voltage will be generated. The error voltage is amplified and used to drive the turret in a direction to null the error voltage.

Figure E-2 is a workable though simplified schematic of only one angle data transmission configuration. It makes little difference whether the CX is on the sight or turret as long as the error signal is taken from the CT at the opposite end of the chain as in Figure E-3.

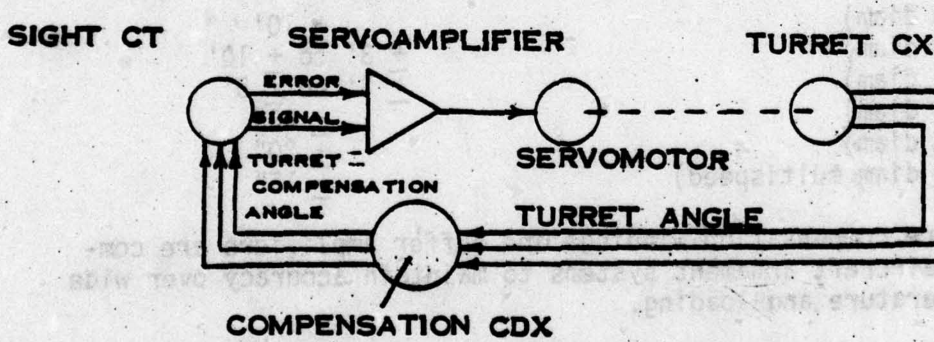


FIGURE E-3. Error Signal Taken from Sight Synchro

Possible advantage of the configuration shown in Figure E-3 is that the low level error signal is not generated in the noisy turret environment and the wiring run to the servoamplifier might be shorter.

Four wire resolvers have nearly supplanted the three wire synchros in aircraft armament systems although the synchros are still used for many angle measurement applications. The devices differ in the number and spacing of windings. Resolver windings are in quadrature or spaced at 90 degrees electrically (and physically in single speed units). Schematics of several resolver types are shown in Figure E-4. Electrical outputs are sine and cosine functions of the shaft angle.

Additional resolver types include RXs and RCs with one rotor winding and RXs with two windings but one lead common to both windings. Multispeed resolvers are available which provide two electrical outputs for coarse and fine angle measurement but these are not normally necessary for the accuracy expected of aircraft armament subsystems.

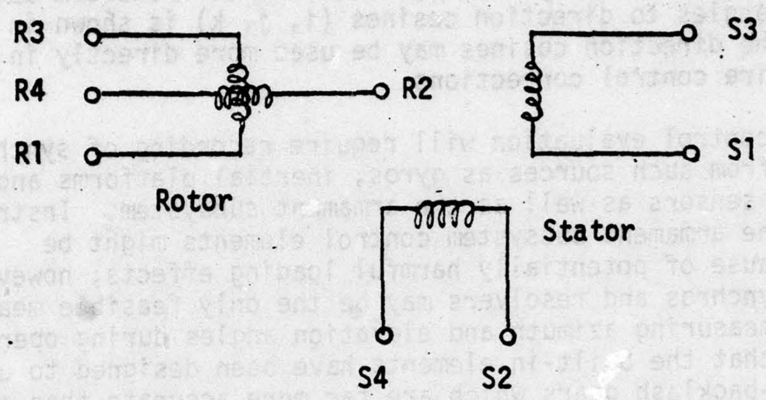
Accuracy of synchros and resolvers varies somewhat with size. Manufacturer's catalogs specify typical accuracies given in Table E-1.

TABLE E-1. Typical Synchro/Resolver Accuracies

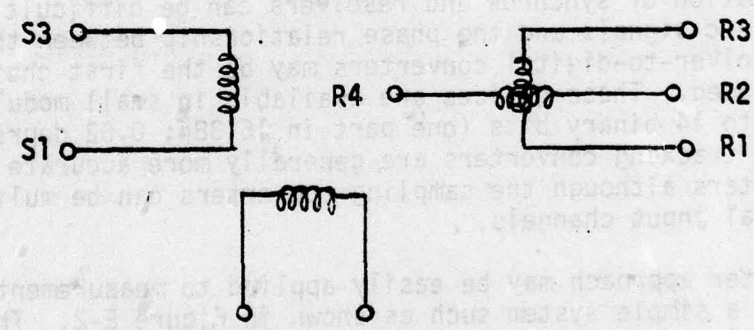
Size (in.)	Accuracy, Minutes and Seconds of Arc
5 (0.500 diam)	± 10'
8 (0.750 diam)	± 3' to ± 10'
11 (1.062 diam)	± 3' to ± 5'
15 (1.437 diam)	± 40"
25 (2.478 diam)	± 20"
78 (7.750 diam multispeed)	± 15"

Temperature compensation windings and buffer amplifiers are commonly used in aircraft armament systems to maintain accuracy over wide ranges of temperature and loading.

The similarity of 3-wire synchros to 4-wire resolvers is evidenced by two devices that can change synchro signals to resolver signals and vice versa. The transolver is a marriage between synchro and resolver and can accept physical angular inputs as well as electrical. The Scott-T transformer on the other hand has no provision for a rotary shaft and merely converts the electrical signals.



a. Resolver transmitter, RX



b. Resolver differential, RD and Resolver control transformer, RC

FIGURE E-4. Resolver Types

A schematic of a fire control data transmission system (similar to the M28A1) which employs computing resolvers to transform azimuth and elevation angles to direction cosines (i, j, k) is shown in Figure E-5. The direction cosines may be used more directly in implementing fire control corrections.

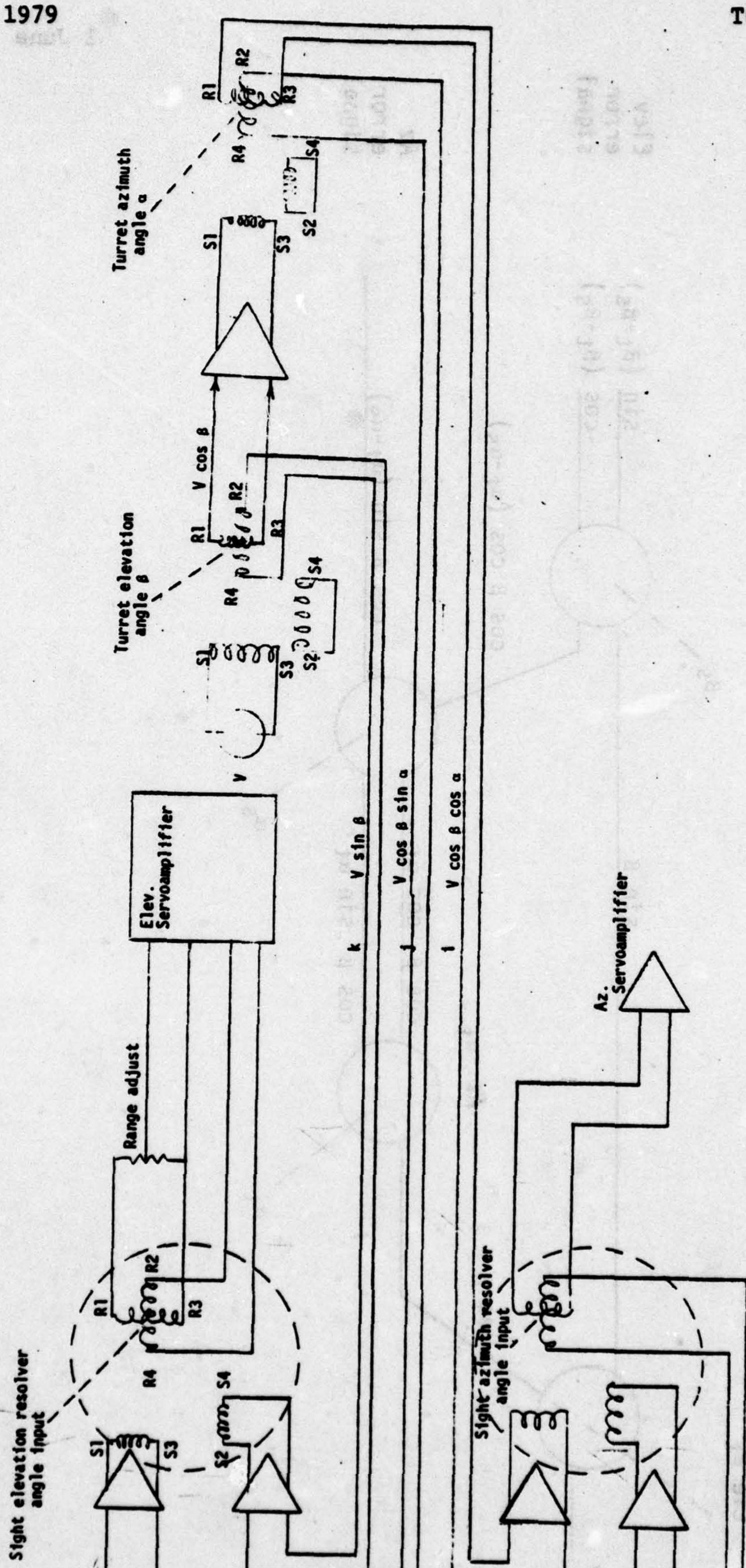
The fire control evaluation will require recording of synchro angle signals from such sources as gyros, inertial platforms and wind direction sensors as well as the armament subsystem. Instrumentation of the armament subsystem control elements might be questioned because of potentially harmful loading effects; however, the built-in synchros and resolvers may be the only feasible means of accurately measuring azimuth and elevation angles during operation. The reason is that the built-in elements have been designed to use precision anti-backlash gears which are far more accurate than any presently available add-on transducers. The test agency will have to assure the developer that the instrumentation does not adversely affect the test item. This assurance may be provided by using only high impedance taps and by observing no shift in boresight when the instrumentation is switched in and out of the system.

Instrumentation of synchros and resolvers can be difficult because of the a-c signals and the phase relationship between them. Synchro and resolver-to-digital converters may be the first choice if they can be used. These devices are available in small modules with precision to 14 binary bits (one part in 16,384; 0.02 degree) or better. The tracking converters are generally more accurate than sampling converters although the sampling converters can be multiplexed to several input channels.

The converter approach may be easily applied to measurement of sight angles of a simple system such as shown in Figure E-2. The converters can also be used for gyros and wind direction sensors instrumented with control transmitter synchros and resolvers at standard voltages and frequencies (such as 26V, 400 Hz).

A problem with converters arises when resolvers are used to perform coordinate transformations as in Figure E-5. Available converters may or may not accept the voltage levels at the turret resolver outputs.

Analog recording of synchro and resolver signals is seldom satisfactory because of inadequate accuracy and difficulty of data reduction.



Turret azimuth angle α
R1
R2
R3
R4
S1
S2
S3
S4
Turret elevation angle β
V cos β
V
Elev. Servoamplifier
V sin β
V cos β sin α
V cos β cos α
k
i
i
Range adjust
Sight elevation resolver angle input
Sight azimuth resolver angle input
Az. Servoamplifier

FIGURE E-5a

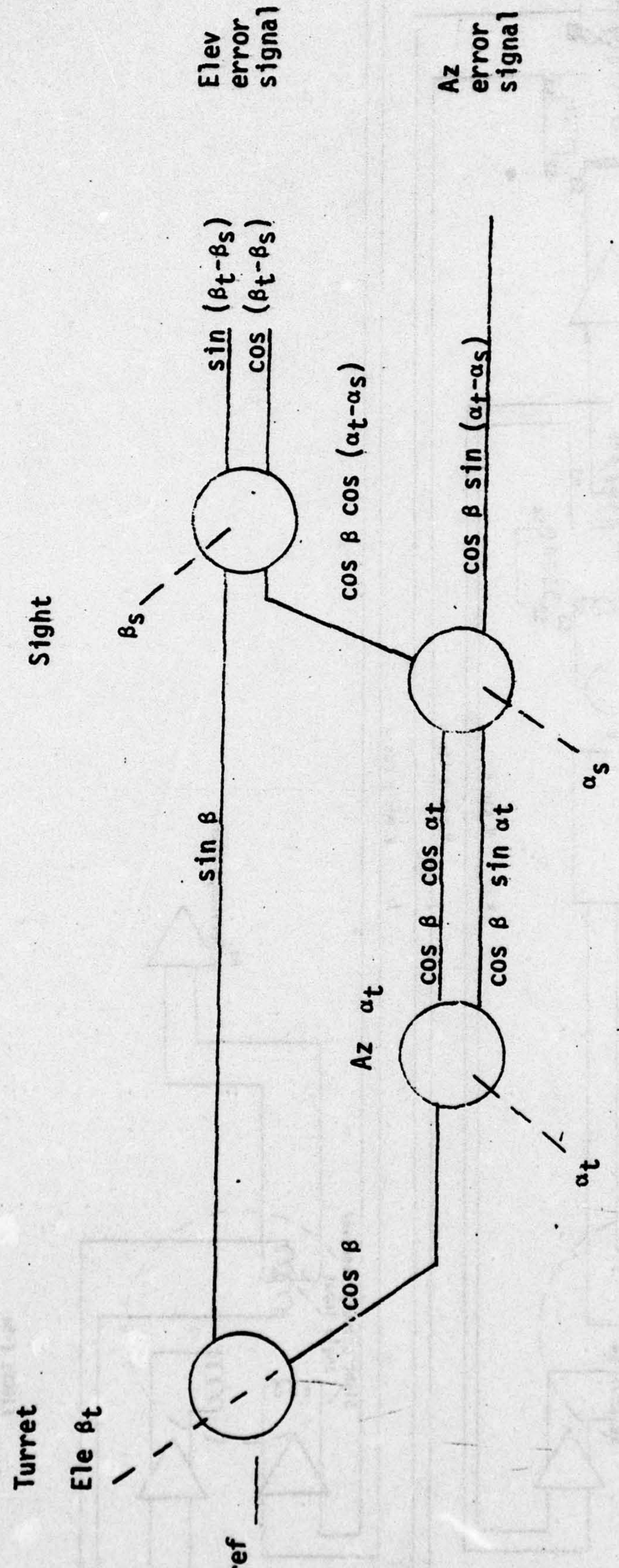

Turret
Ele β_t
V_{ref}
Sight
β_s
Elev error signal
$\sin(\beta_t - \beta_s)$
$\cos(\beta_t - \beta_s)$
$\sin\beta$
$\cos\beta$
Az α_t
α_t
$\cos\beta\cos\alpha_t$
$\cos\beta\sin\alpha_t$
α_s
$\cos\beta\cos(\alpha_t - \alpha_s)$
$\cos\beta\sin(\alpha_t - \alpha_s)$
Az error signal

FIGURE E-5b

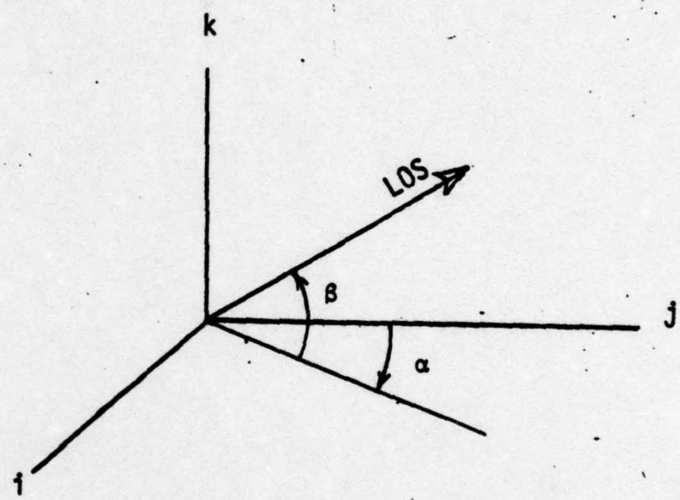


FIGURE E-5c

Digital or PCM recording of the raw signals will create a problem due to aliasing or amplitude change because of phase shift between signal and sample. This can be corrected through use of sample-and-hold amplifiers on each input so that all signals can be sampled simultaneously at the peak reference voltage amplitude.

The desired angles can then be reduced by taking the inverse of the 3-wire synchro signals, the resolver sine and cosine signals, direction cosines or error signals.

Potentiometric control elements have not been used in any aircraft armament systems developed since the M21, probably because of drift and reliability problems.

Optical angle encoders are capable of very high precision but require total digital control and are not likely to be used for aircraft armament in the near future.

APPENDIX F. FREQUENCY ANALYSIS

General

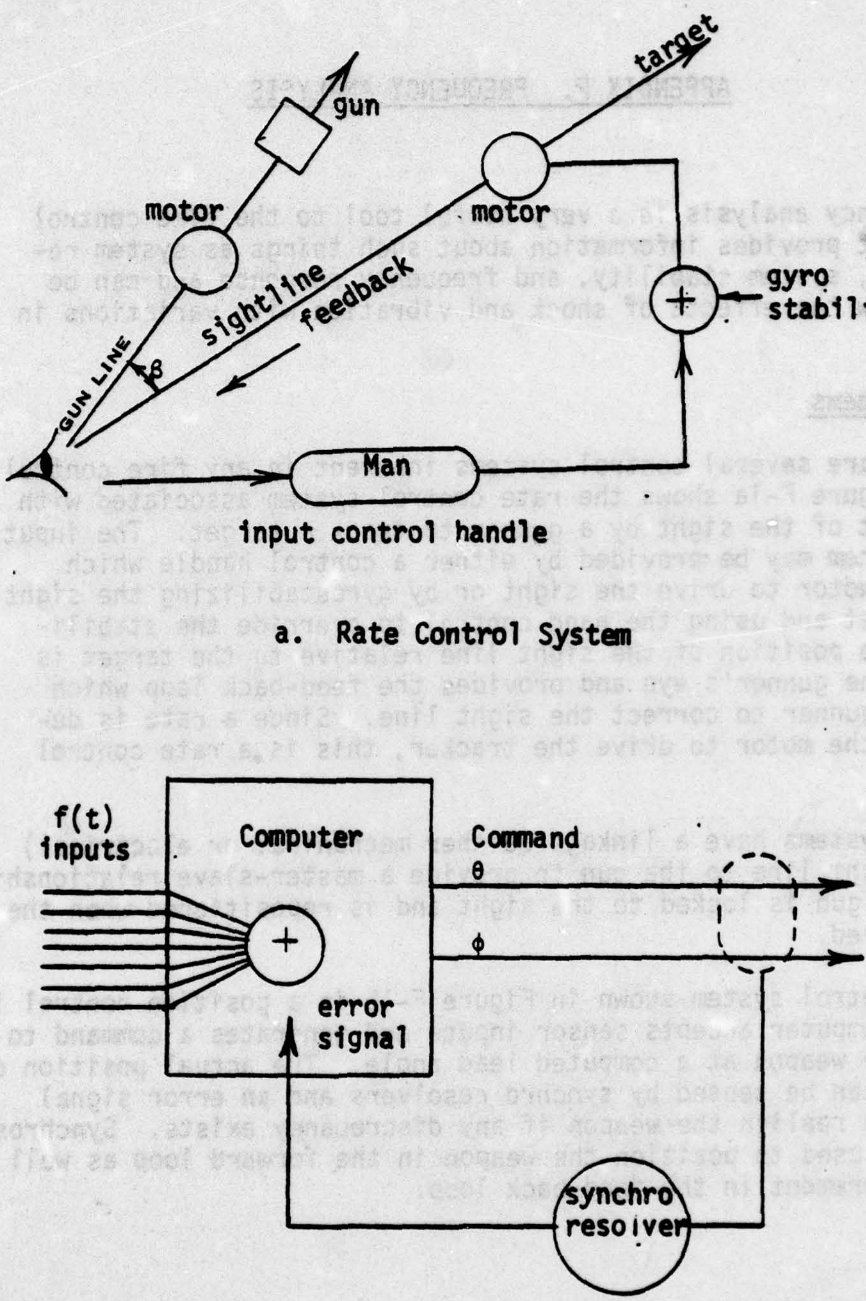
Frequency analysis is a very useful tool to the fire control analyst. It provides information about such things as system response time, system stability, and frequency response and can be used to show the effects of shock and vibration with variations in frequency.

Control Systems

There are several control systems inherent in any fire control system. Figure F-1a shows the rate control system associated with the movement of the sight by a gunner to track a target. The input to this system may be provided by either a control handle which operates a motor to drive the sight or by gyrostabilizing the sight on the target and using the hand control to override the stabilization. The position of the sight line relative to the target is sensed by the gunner's eye and provides the feed-back loop which allows the gunner to correct the sight line. Since a rate is developed by the motor to drive the tracker, this is a rate control system.

Some systems have a linkage (either mechanical or electrical) from the sight line to the gun to provide a master-slave relationship wherein the gun is locked to the sight and is repositioned when the sight is moved.

The control system shown in Figure F-1b is a position control in which the computer accepts sensor inputs and generates a command to position the weapon at a computed lead angle. The actual position of the weapon can be sensed by synchro resolvers and an error signal generated to realign the weapon if any discrepancy exists. Synchros may also be used to position the weapon in the forward loop as well as for measurement in the feed-back loop.



a. Rate Control System

b. Position Control System

FIGURE F-1. Fire Control

A control system may be represented by a block diagram as shown in Figure F-2. The input-output relationship can be described by a sinusoidal transfer function, a complex function of the frequency ω, characterized by its magnitude and phase angle, with frequency as the parameter.

There are two transfer functions that will be considered. The open-loop transfer function G(jw) H(jw) is the transfer function obtained by breaking the connection at point "b" and measuring the response to an input at point "a", i.e. the response of the system before the feed-back loop is closed. It is useful because it is amenable to measurement and can be used to predict certain characteristics of a control system, such as stability.

The closed-loop frequency response

$$\frac{C(jw)}{R(jw)} = \frac{G(jw)}{1 + G(jw)\ H(jw)}$$

represents the response to a given input excitation with a measure of the output feed-back to the input for comparison.

Both functions may be determined by precisely measuring the response of the fire control system to an input consisting of sinusoidal test signals. One representation of these sinusoidal transfer functions is the Bode diagram (Figure F-3) consisting of two graphs (only the closed-loop transfer function is plotted).

One graph is the plot of the logarithm of the magnitude of the sinusoidal transfer function; the other is a plot of the phase angle. Both are plotted against the frequency in logarithm scale (semilog).

Bode plots may be applied to the open-loop transfer function to determine whether or not a system is stable. The gain crossover frequency W_G is the frequency at which the magnitude of the open-loop transfer function is unity. The phase margin is that amount of additional phase lag at the gain crossover frequency (0 dbgain) which is needed to bring the phase to 180 degrees. At this point the gain is 1 and the phase angle equals 180 degrees; hence, G(jw) H(jw) = -1 + Jo and the relationship C(jw)/R(jw) blows up, indicating instability. The phase margin then equals 180 degrees plus the phase angle of the open-loop transfer function at the gain crossover frequency, or $\gamma = 180 + \phi$. These are illustrated further in Figure F-4 for a stable system (a) and an unstable system (b).

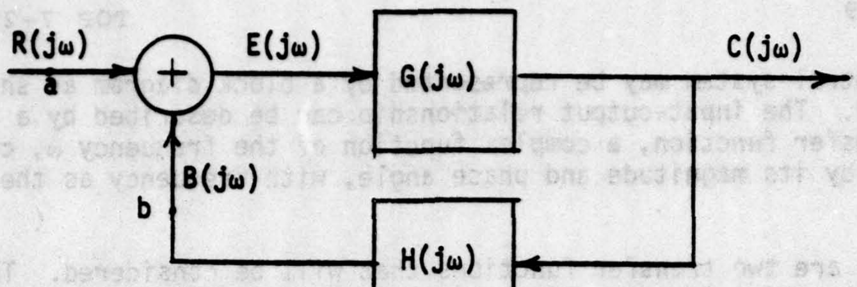


FIGURE F-2. Control System Block Diagram

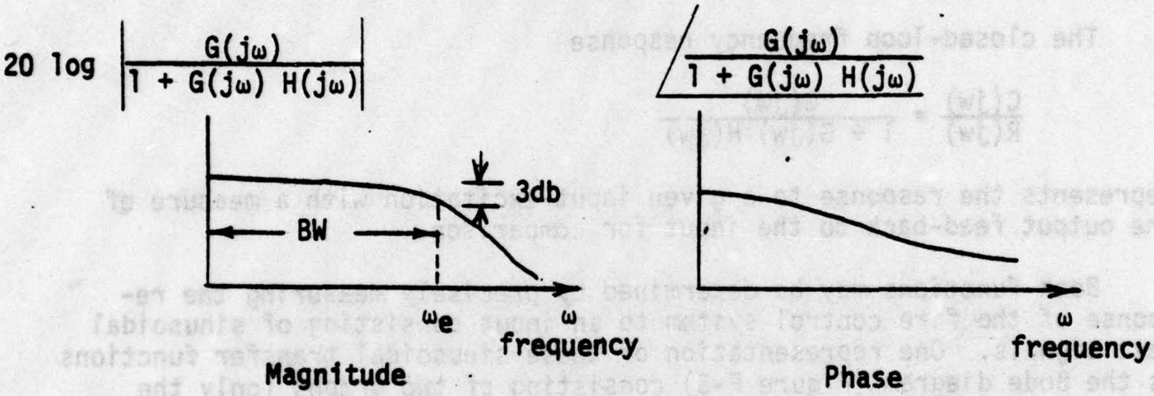
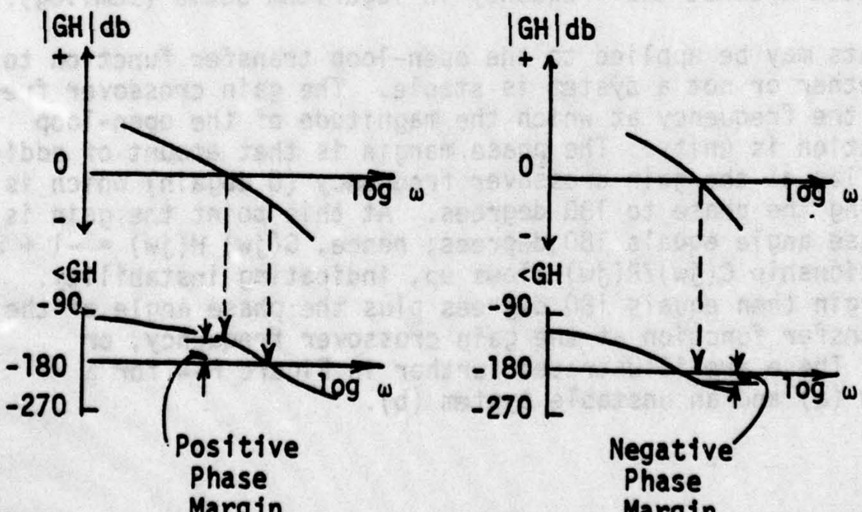


FIGURE F-3. Bode Diagrams for the Closed-Loop Transfer Function



a. Stable System b. Unstable System

FIGURE F-4. Bode Plots

The frequency at which the magnitude of the closed-loop frequency response is 3 db below its zero frequency value is called the cutoff frequency W_c (Fig. F-3). The closed-loop system filters out the signal whose frequencies are greater than the cutoff frequency and transmits those signals with frequencies lower than W_c. The system bandwidth is the frequency range $o \leq \omega \leq \omega_c$. It gives an indication of the speed of response of a control system by an inverse relationship. A system should have a large bandwidth to follow arbitrary inputs accurately; however, a large bandwidth requires high performance components which are expensive. Also, from the point of view of noise, the bandwidth should not be too large since this causes jitter in the system. Therefore, a compromise must be reached between desired cost, noise, and accuracy considerations.

The cutoff rate is the slope of the Bode plot near the cutoff frequency. It indicates the ability of the system to distinguish the signal from the noise.

There are other convenient representations of the sinusoidal transfer function but their description is beyond the scope of this TOP. The reader is referred to Reference 4 for more details on the use of frequency analyses in evaluating control systems.

A transient analysis of a control system is necessary to be certain that the transient response is satisfactory. This may be determined by measuring the system response to certain driving functions, e.g. the performance characteristics may be stated in terms of the system response to a unit step function (see Figure F-5). Some important quantities are per cent overshoot, rise time, settling time, and delay time.

The per cent overshoot is the percentage of the final value by which the output exceeds the input. The rise time is the time required for the system to go from 10 percent to 90 percent of the final value. Settling time is the time required for the system to settle to within 5 percent of the final value. Delay time is the time required for the system to reach 50 percent of its final value.

The system response to other functions, such as ramp and impulse functions is also of interest. The reader is referred to Reference 4 for a detailed discussion of transients in control systems.

In practice the closed-loop frequency response is usually the most conveniently obtainable, and it provides most of the information required concerning the performance characteristics of the control system. For example, if a large step function is input to the system, the slope of the response yields the maximum velocity ($\Delta D/\Delta t$), the maximum acceleration ($\Delta V/\Delta t$), the time delay (Δt at 50%), time to reach maximum velocity and acceleration, and the settling time of the system. If a small, constant magnitude, sinusoidal forcing function is used, the response plots (gain and phase) directly yield the cutoff frequency (maximum reliable rate of change) range of reliable control (bandwidth), the phase relationship between input and output and the peak response frequency (point of maximum gain).

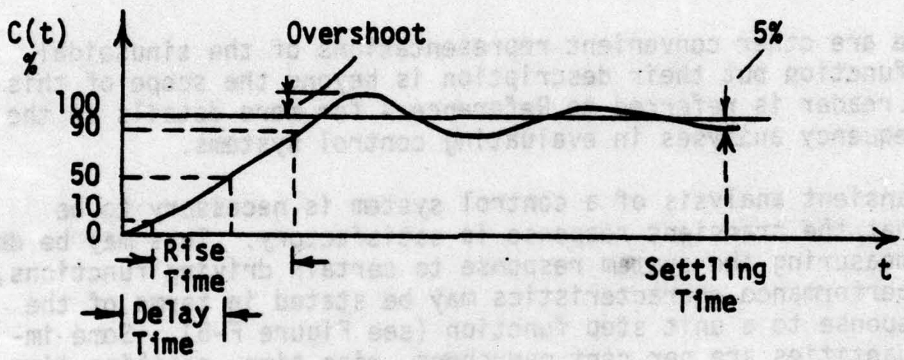


FIGURE F-5. Unit Step Response

APPENDIX G. REFERENCES

1. AMCP 706-191, Engineering Design Handbook, System Analysis and Cost Effectiveness, 1971

2. TOP/MTP 4-2-604, Range Firings of Small Arms Ammunition

3. TOP/MTP 4-2-805, Projectile Velocity Measurements

4. TOP/MTP 4-2-827, Time of Flight and Ballistic Coefficients

5. Special Study of Procedures for Accuracy Evaluation of Partial-Solution Helicopter Fire Control Subsystems Under Typical Flight Conditions, Final Report by Myron J. Ross and Morris W. Hutchins, Aberdeen Proving Ground, Maryland, July 1972

6. AMCP 706-327, Engineering Design Handbook, Fire Control Series, Section I, Fire Control Systems - General, January 1968

7. AMCP 706-113, Engineering Design Handbook, Experimental Statistics, Section 4, Special Topics

8. McIntire, Thomas O., Fire Control Sensitivity Analysis Using a Programmable Calculator, ARO Report 75-2 from Proceedings of the Twentieth Conference on the Design of Experiments in Army Research Development and Testing, January 1975.